AN EXPERIMENTAL STUDY OF THE FLOW OF A
TURBULENT BOUNDARY LAYER OVER A STEP AT M=2.35

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SUMMARY

An experimental study of the interaction phenomena caused by the flow of a turbulent boundary layer over a step was conducted at a Mach number of 2.35. The step height, which was the only parameter varied, was increased from 1/4 to 1-3/4 boundary layer thicknesses. Measurements were made of the static pressure distribution along the wall in front of the step, and detailed total head surveys were made through the interaction.

The obstruction of the flow of the turbulent boundary layer by a step caused the generation of compression waves, initially within the boundary layer, which coalesced into an oblique shock outside the boundary layer. The flow near the wall experienced first a steep pressure rise and then a continuously decreasing pressure gradient until a maximum pressure was reached ahead of the step. Separation of the flow from the surface occurred for all steps greater than 1/4 boundary layer thickness in height at a pressure ratio of about 1.80. The location of important details of the interaction appear to bear a linear relationship with the step height, occurring further forward of the step as step height increases.

For small steps the interaction occurred in a short distance and the initial pressure rise was very steep. The interaction spread out and the initial (maximum) pressure gradient decreased as step height was increased. The maximum pressure ratio increased with step height but appeared to be leveling out to a constant peak value of 2.2 as the step height approached two boundary layer thicknesses.

A comparison of the results of this investigation with those of a similar investigation at M=2.92 revealed that the length of the interaction, the pressure ratio required for separation, and the peak pressure ratio are increasing functions of the Mach number.

INTRODUCTION

The advent of modern day supersonic aircraft and the increasing application of supersonic flow devices in many fields make mandatory the development of a method of predicting the deviations of the viscous flow of real fluids from the potential flow solutions in this flow range. The cost of the trial and error experimental method of designing such complex items as supersonic compressors or supersonic inlets would be prohibitive. The experience and results obtained in the design of one object, in general, cannot be directly applied to the design of another. What is required is a complete knowledge of the behavior of laminar and turbulent boundary layers in the presence of an external supersonic flow field. Of particular importance are the effects on the boundary layer flow of the adverse pressure gradients associated with the presence of shock waves.

Theoretical studies (reference 1-5) have been made of supersonic boundary layer flow in adverse pressure gradients. However, all of these analyses depend on obtaining certain factors from experimental results. A number of experimental investigations of the separation of laminar and turbulent boundary layers (references 6-16) have been conducted. In the case of laminar boundary layers sufficient data has been made available to indicate that the theoretical work roughly predicts the phenomena. But data on the separation of turbulent boundary layers is limited. A detailed experimental program is in progress at the Gas Dynamics Laboratory of the James Forrestal Research Center, Princeton University. The purpose of this program is to provide a complete and consistent set of data, covering a range of Mach numbers, of the characteristics of the flow of a turbulent boundary layer in the presence of shock waves. The results of initial experiments at a nominal Mach number of 3 have been published (references 17-20). Other tests

at Mach numbers of approximately 3.8 and 1.3 to 1.8 are being completed and the results are being prepared for publication.

The objective of this thesis is to further the development of a detailed model of the separation phenomena by providing data at a Mach number of 2.35. In these tests, the turbulent boundary layer was caused to separate by placing steps of varying height on the tunnel wall in the path of the flow. Details of the phenomena resulting from the obstruction to the boundary layer flow were investigated by 1) measuring the static pressure distributions on the tunnel wall, and 2) making total head surveys in the interaction region.

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NOMENCLATURE

X - Distance measured along tunnel wall from face of step - inches

Y - Distance measured perpendicular to wall - inches

h - step height - inches

P - local static pressure

P_1 - free stream static pressure

P_O - chamber pressure

P_T - total head pressure

M - Mach number

V - velocity

δ - boundary layer thickness - inches

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

The tests reported herein were performed in the Princeton University pilot supersonic wind tunnel (reference 21). This wind tunnel is of the intermittent or blowdown variety, utilizing air stored at 3000 psi in tanks of a central storage system having a total capacity of 1700 cubic feet. A regulator between the storage tanks and the tunnel permits operation at stagnation pressures between 75 psi and 900 psi. The stagnation pressure for these experiments was set at approximately 75 psi. A Mach number of about 2.35 was attained in a test section of nominal dimensions 2 inches wide by 1-$\frac{1}{2}$ inches high.

A series of seven steps which spanned the tunnel to within .010" of each side wall, were used to obstruct the flow of the fully turbulent boundary layer on the tunnel wall and thereby cause the interaction phenomena. These steps varied in height from .050" to .350" at intervals of .050". The unobstructed boundary layer thickness at the test section was approximately .20 inches; hence these steps caused a range of obstructions from 1/4 to 1-3/4 boundary layer thicknesses in height. The steps were attached to a support mounting which was driven axially along the tunnel by a micrometer (figures 1 and 2), permitting longitudinal positioning to within .005" of a desired setting. A thin balsa wood strip was inserted into the bottom forward portion of each step to act as a seal and a bearing surface. The tunnel wall has a slight curvature at the test section, and it was found necessary to incorporate a spring-pivot arrangement in the mounting mechanism to insure that the steps remained firmly on the tunnel wall. As a precaution against inadvertent leakage under the step, the static pressure was measured through an orifice on the lower face of each step (with the exception of the .05" step) during every run.

The wall static pressure distributions were determined by passing the interaction over a single .030" orifice on the centerline of the tunnel wall. `This procedure avoided the errors inherent in the use of numerous orifices and permitted freedom in the spacing of data points. Two dimensionality of the phenomena was checked by the use of additional spanwise static pressure orifices, located 3/8", ½", 5/8", and 3/4" off the centerline but at the same longitudinal station as the main orifice. Lack of two dimensionality was not encountered in these tests.

Total pressure surveys were made parallel and perpendicular to the tunnel wall. The total head probe employed is of minute dimensions (figure 2) so as to prevent so far as possible any interference with the interaction. The probe consists essentially of three sections, a head, neck, and tubing stem. The stem is 3/32" stainless steel tubing. Silver soldered to the stem is a flattened stainless steel neck with sharp leading and trailing edges. The neck is .4" in height and has a maximum cross-stream dimension of .025". ·The head, which extends .25" forward of the centerline of the neck and stem, is tapered; and its tip is honed and flattened on the upper and lower surfaces. The tip is .004" high and has a wall thickness of .003", thereby permitting readings to within .005" of the surface. A micrometer drive was utilized to position vertically the total head probe; positioning was accurate to within .001". The neck and stem of the probe moved through an insulated sleeve in the tunnel floor. The probe could be set facing either upstream or downstream. An electrical contact permitted determination of the "just touching" position of the head of the probe with the tunnel wall. This position was established for each survey with the tunnel running. Significant variation was noted in the static pressure during one of the total head surveys perpendicular to the tunnel wall.

It was suspected that the probe might be interfering with the interaction at this particular step location. Therefore, a rerun was made at this location employing a probe of similar construction but which extended .4" forward of the centerline of the stem. No significant variation of the static pressure was found with this new probe, and the total pressure data of the previous run was verified.

RESULTS AND DISCUSSION

The static pressure distributions along the tunnel wall for the various steps employed are shown in figures 3 through 9. A composite of these curves is presented in figure 10 for direct comparison. The face of the step is the zero reference and distances upstream are taken as negative. All the distributions are characterized by a steep initial pressure rise, followed by a continuously decreasing pressure gradient until a maximum pressure ahead of the step is reached. Following the maximum pressure point, a dip in the curve occurs for all steps except the .05" step. There is another steep pressure rise immediately in front of the step. It is believed that the presence of a strong vortex in the corner is the cause of the dip in the pressure curve (see reference 19).

The length of the interaction, as measured between the start of the initial pressure rise and the maximum in the pressure distribution curve, is seen to vary considerably with step height. For the .05" step this distance is of the order of two boundary layer thicknesses, but for the .30" step the length of the interaction has increased to nearly six boundary layer thicknesses. The steepness of the initial pressure rise proceeds in the other direction, being greatest for the smallest step and decreasing as step size increases. The maximum pressure attained prior to the dip in the curve

increases with step height, but tends to level out to a constant value for the larger steps. It may be noted that the data is incomplete for the .30" and .35" steps. Forward movement of these steps was restricted by tunnel choking conditions.

The undisturbed boundary layer profile at the test section was determined by a total head survey perpendicular to the tunnel wall with the tunnel free of obstructions. At this location the boundary layer thickness is about .20", the displacement thickness .0403", and the momentum thickness .0108". The Reynolds number per inch was calculated to be approximately 1.68×10^6.

The separation phenomena was studied by making horizontal total head surveys close to the tunnel wall at varying longitudinal distances from the face of the step for all step heights. Surveys were made with the probe positioned at Y=.010" and .025" above the surface (approximately 1/20 and 1/8 of a boundary layer thickness, respectively). The X distance in front of each particular step where the total and static pressures were the same is that location at which zero velocity occurs at the set probe height. A linear extrapolation of the corresponding X and Y distances was used to determine the distance in front of each step where the flow separates from the surface. The basis for this linear extrapolation will be discussed later. With the known separation distance ahead of a step, the corresponding pressure ratio required for separation may be evaluated by reference to the static pressure distribution curve.

Mach number distributions .010" above the wall for the various steps are shown in figures 11-17. The Mach numbers were obtained by applying the conventional pitot-static relationships to the measured total pressure and wall static pressure at each station. Forward movement of the step was

limited by the presence of the probe and thereby precluded the determination of a complete Mach number distribution curve for the .05" step. The curves for all the steps are similar and exhibit a rapid deceleration of the flow near the surface. Only distances of two to three boundary layer thicknesses are required for completely stopping the flow.

A detailed investigation was made of the flow over the .25" step. Total head surveys normal to the tunnel wall at various distances from the face of the step were made with the probe facing both upstream and downstream. The measured total head profiles at various distances forward of the step with the probe facing upstream are presented in figure 18. The lower portions of the measured total head profiles obtained first with the probe facing upstream and then downstream are shown in figure 19. A schematic drawing of the interaction phenomena in juxtaposition with the static pressure distribution for the .25" step is shown in figure 20.

The profile at station -1.60" (figure 18) is identical to that of the undisturbed boundary layer profile found in the free tunnel survey. Up to station -1.30" the profile shape has not been altered significantly although the wall static pressure has increased more than 30% of its initial value. At station -1.20" the characteristic rapid deceleration of the lower portion of the boundary layer which preceeds separation first becomes evident. The flow is separated from the surface at all subsequent stations shown in figure 18. The existence of compression waves resulting from the interaction is made manifest by the presence of the "bulge" in the total head profile at X=-1.10". At this station the "bulge" is well within the initial boundary layer thickness and results from compression waves generated within the boundary layer prior to separation. Further downstream this "bulge" grows and flattens until at about X=-.80", where the extent of the separation is

large, it is possible to clearly distinguish several flow regions. There is
a deep mixing region, a nearly uniform flow, and then a shock as evidenced
by the "break" in the total head curve. This shock has been formed by the
coalescing of compression waves generated by the interaction. At about
X=-1.00" a few compression waves have come together just outside the boundary
layer to form a weak shock. This shock increases in strength out from the
wall as the process of coalescence continues downstream. For example, using
the measured total head values, the shock strengths at stations -0.80" and
-0.60" were calculated to be 1.97 and 2.08, respectively. Using the shock
pressure ratio at X=-0.80", the static pressure in the nearly uniform stream
behind the shock was determined to be about 4% less than the static pressure
at the surface.

That separation occurs between stations -1.20" and -1.10" is
verified in figure 19. The curves shown are of value only in distinguishing
regions of reverse flow and the physical location of the zero velocity
contour. The presence of reverse flow is indicated by a lower total head
reading when the probe is facing upstream than when it is facing downstream
at the same vertical setting. When the readings are the same, the velocity
is zero. There is no reverse flow at X=-1.20", but a reverse flow region
extends out to Y=.012" at X=-1.10". The reverse flow region grows in depth
as the step is approached. The maximum Mach number in the reverse flow
region increased downstream to a value of about .48 at the last station
surveyed. It happens that the zero velocity contour is linear as far as the
detailed surveys were taken (X=-.30" and Y=.105"). Hence the justification
of the linear extrapolation, close to the wall, used to determine the X
location where separation of the flow from the surface occurs.

The distances in front of the step for the occurrence of
significant details of the interaction phenomena are plotted against step

height in figure 21. The locations shown are those of the beginning of the interaction which is defined as the point where the wall static pressure first shows an increase, the maximum pressure gradient, the extrapolated separation point, and the maximum pressure point. The locations of these items seem to bear a linear relationship with step height, the distances from the step increasing with increase in step height. Also quite evident is the spreading out of the interaction with increase in step height.

Shown in figures 22 and 23 are the variations with step height of maximum pressure gradient, pressure ratio for zero velocity at Y=.010", the separation pressure ratio, and the maximum pressure ratio. The maximum pressure gradient decreases and the maximum pressure ratio increases with increasing step height. The separation pressure ratio, however, is independent of step height and has a value of 1.80. The extrapolation procedure used is considered to result in accuracies in distance of X=±.2" and in pressure ratio of ±.02. The maximum pressure ratio appears to be leveling out to a constant value of about 2.2 as the step height approaches two boundary layer thicknesses. This value of peak pressure ratio at M=2.35 is in agreement with that predicted in figure 5 of reference 5.

Qualitatively the results of this investigation agree with those obtained in the step studies at M=2.92 (reference 19). The length of the interaction is somewhat greater at the higher Mach number. The peak pressure ratio at M=2.92 was 2.6. The separation pressure ratio evaluated at Y=.010" was reported as 2.1. When extrapolated to the surface, the separation pressure ratio at M=2.92 is found to about 1.95. A comparison of these values with those found in the present investigation shows that both the peak pressure ratio and the pressure ratio required for separation increase with increasing Mach number.

CONCLUSIONS

The conclusions drawn from this experimental study are as follows:

1) The flow of a turbulent boundary layer over a step at a Mach number of 2.35 is characterized by a steep initial pressure rise, followed by a continually decreasing pressure gradient until a maximum pressure ahead of the step is reached. With step heights greater than 1/4 boundary layer thickness, there is a rapid deceleration of the inner regions of the boundary layer which results in the occurrence of separation of the flow from the surface within two to three boundary layer thicknesses.

2) The location forward of the step of the significant details of the interaction phenomena (beginning, maximum pressure gradient, separation, and maximum pressure) seem to bear a linear relationship with step height. As the step height is increased, the locations move further forward of the step.

3) The length of the interaction increases with step height, being of the order of two boundary layer thickness for the .05" step and six boundary layer thicknesses for the .30" step. Correspondingly, the maximum pressure gradient is greatest for the smallest step and least for the largest step.

4) The pressure ratio required for separation is independent of step height and has a value of about 1.80.

5) The maximum pressure ratio increases with step height but appears to be leveling out to a constant value of 2.2 as the height approaches two boundary layer thicknesses.

From a comparison of these results with those of reference 19, it is concluded that the length of the interaction, the separation pressure ratio, and the peak pressure ratio are increasing functions of Mach number.

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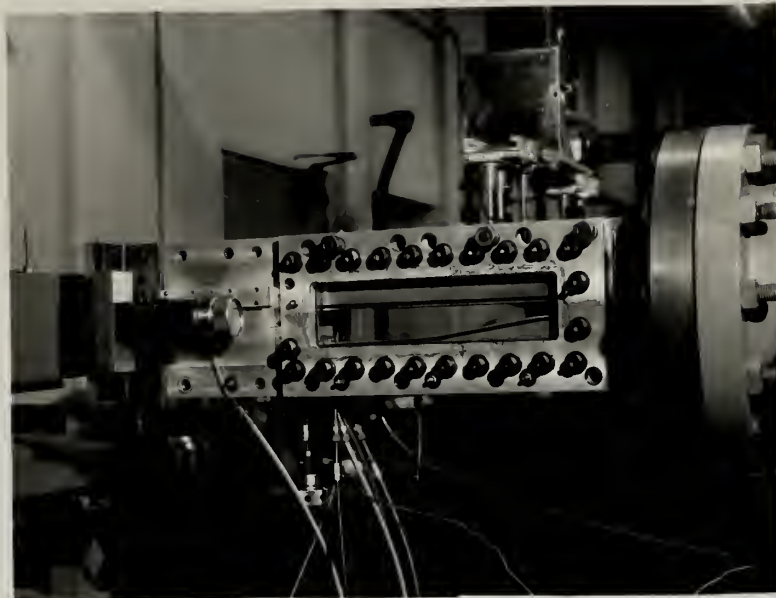
Figure 1   Experimental Installation in Wind Tunnel;
            Showing Step, Total Head Probe, and
            Micrometer Drive Systems for Step and Probe
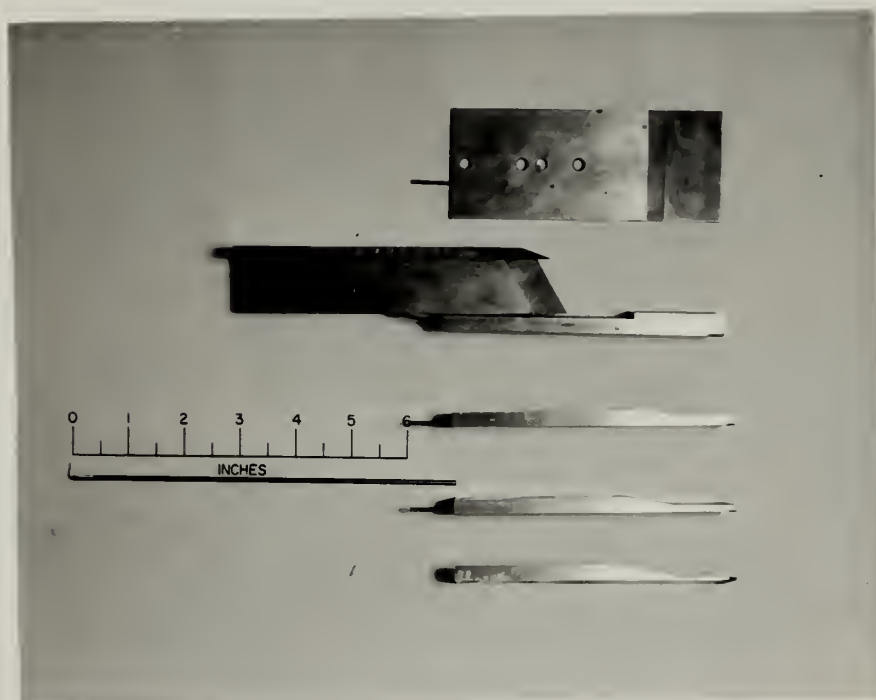
Figure 2   Total Head Probe, the Various Steps Used,
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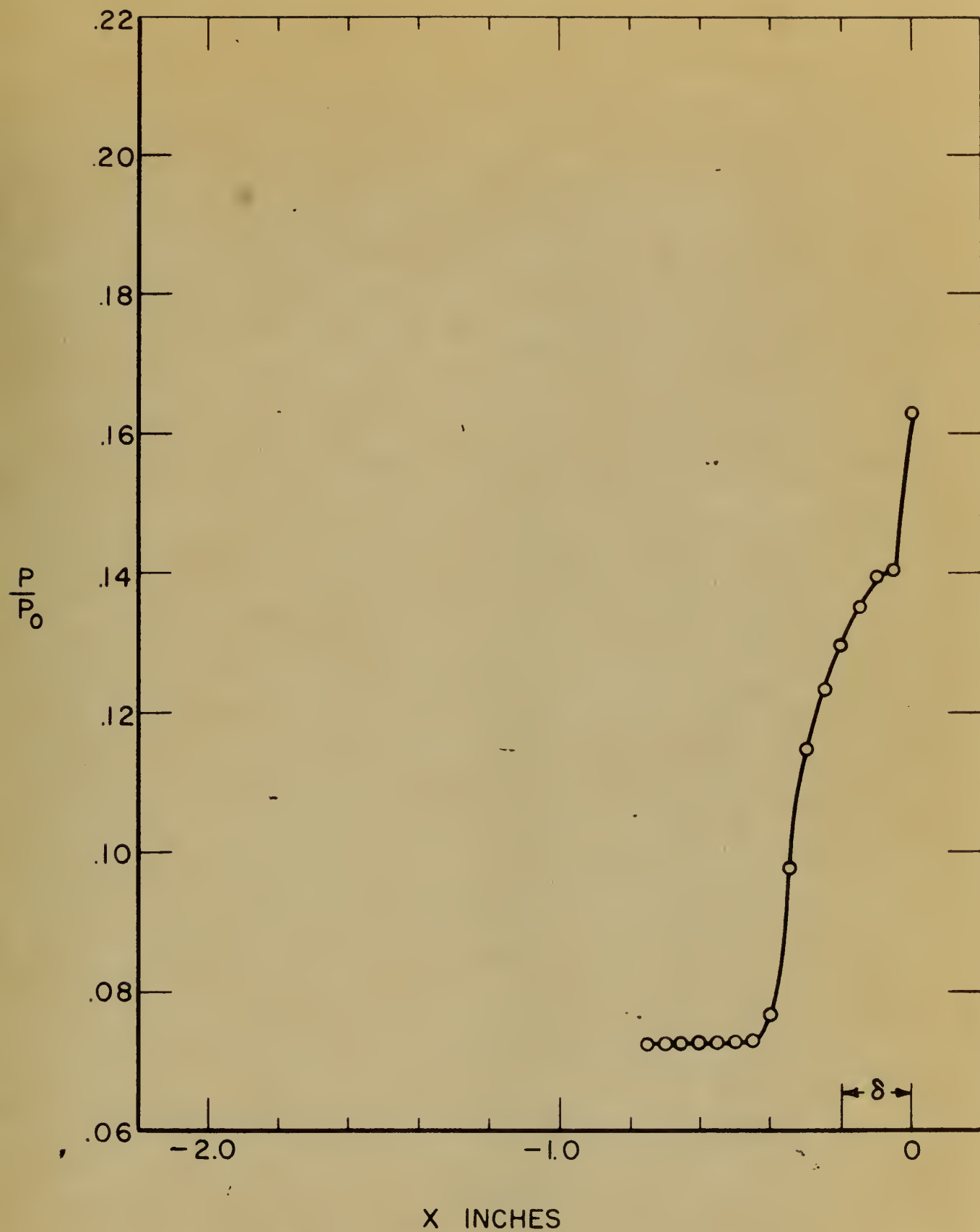
Figure 3 Wall Static Pressure Distribution for .05" Step
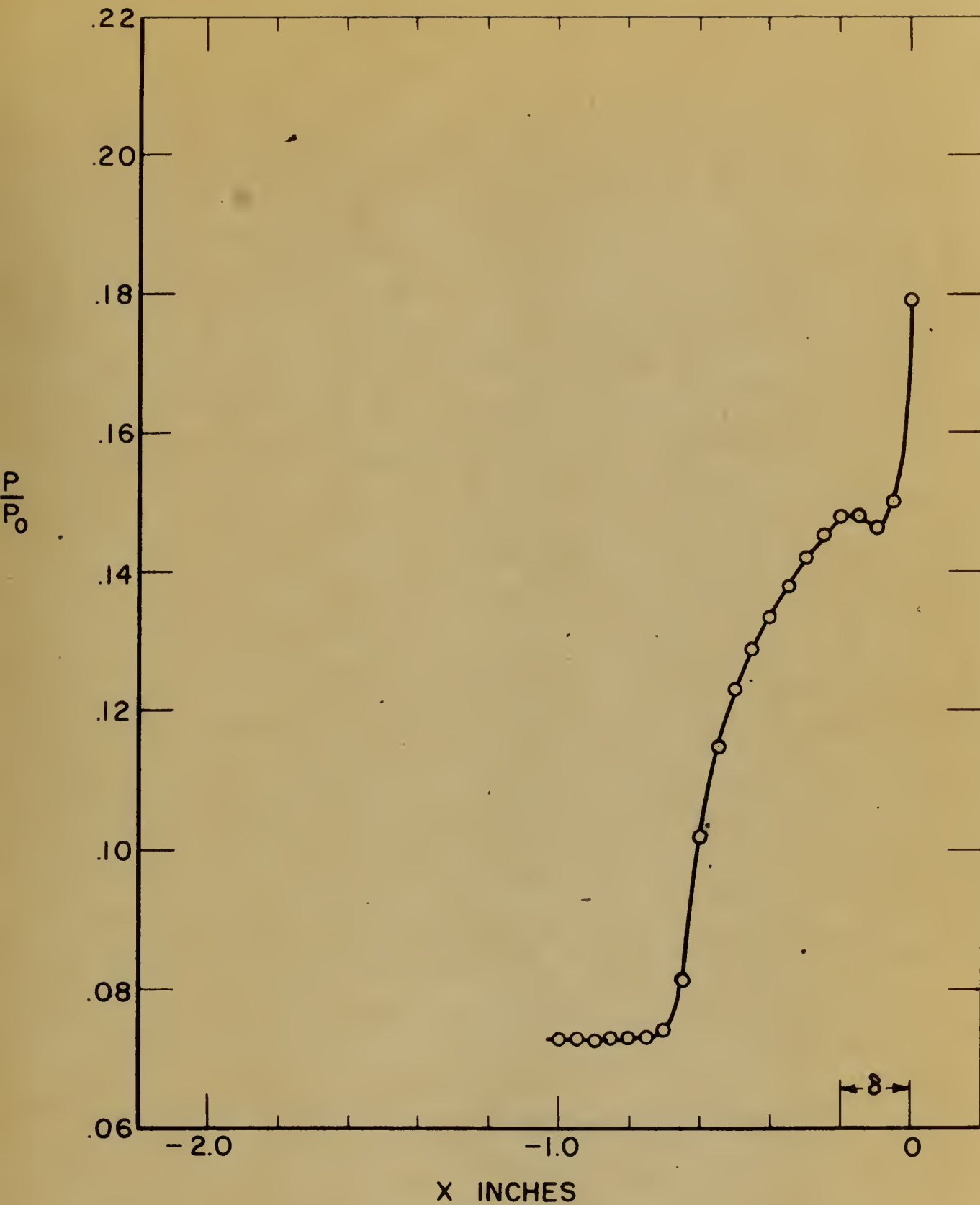
Figure 4   Wall Static Pressure Distribution for .10" Step
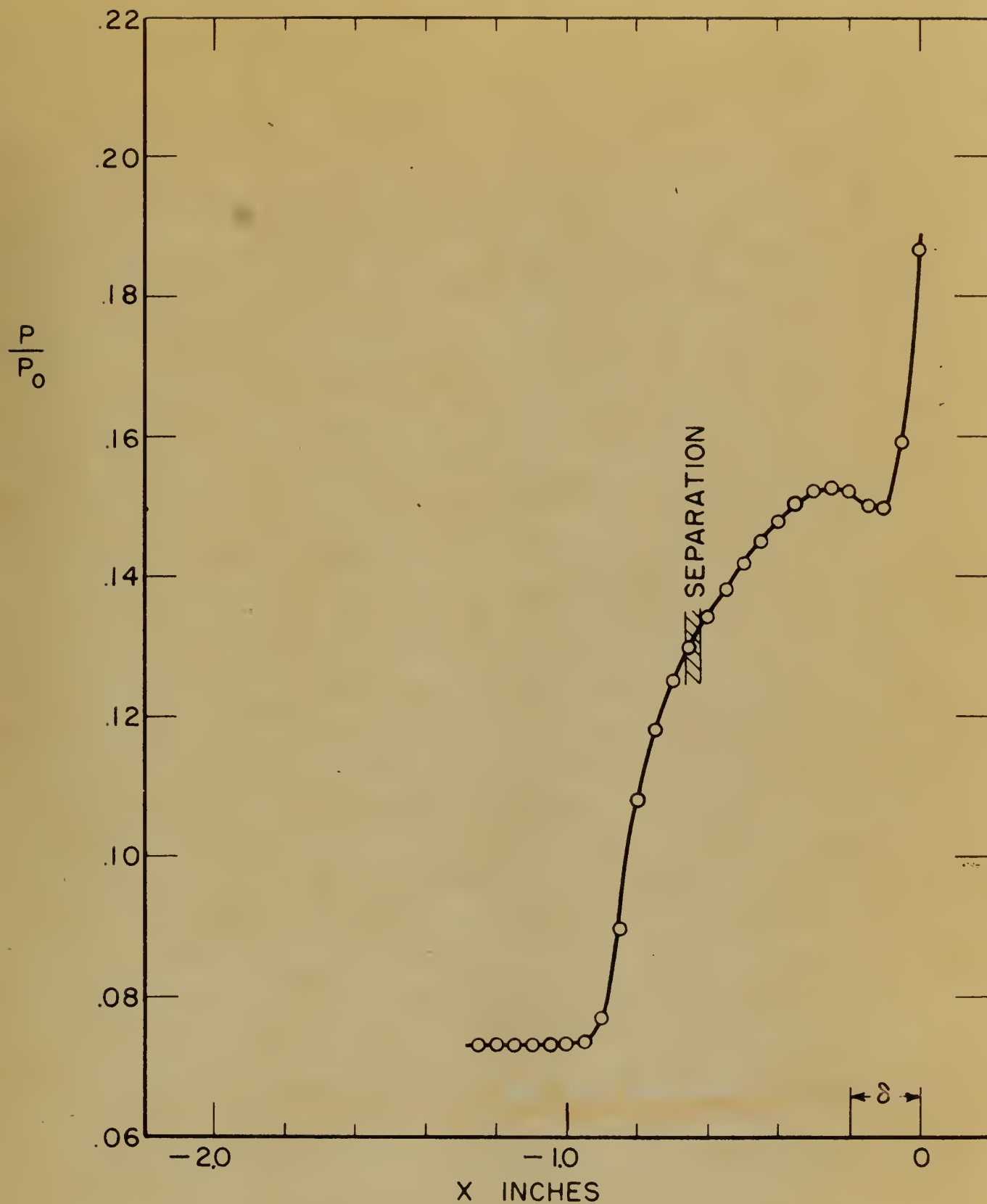
Figure 5. Wall Static Pressure Distribution for .25 Wedge
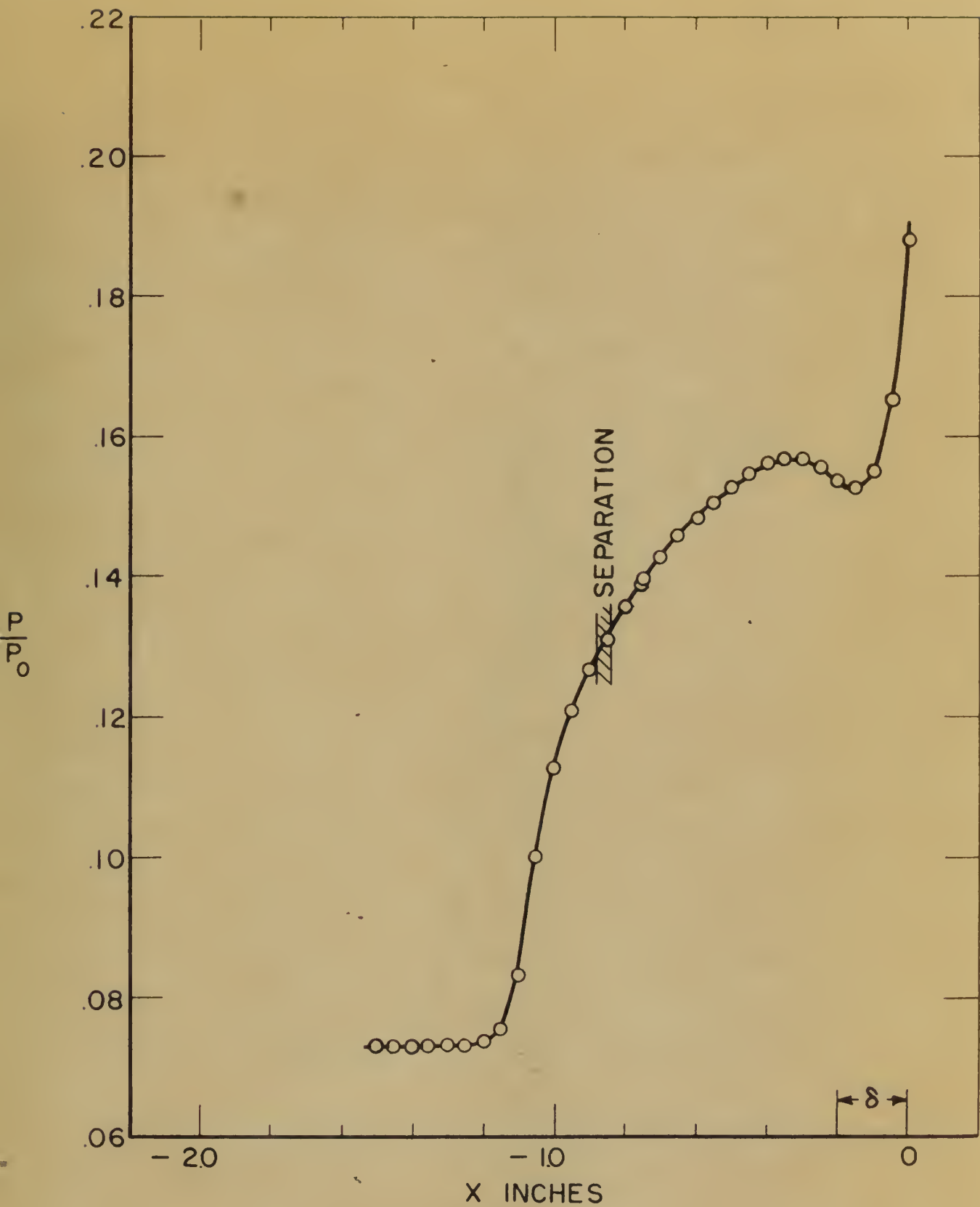
Figure 8. Wall Static Pressure Distribution for "SL" Step
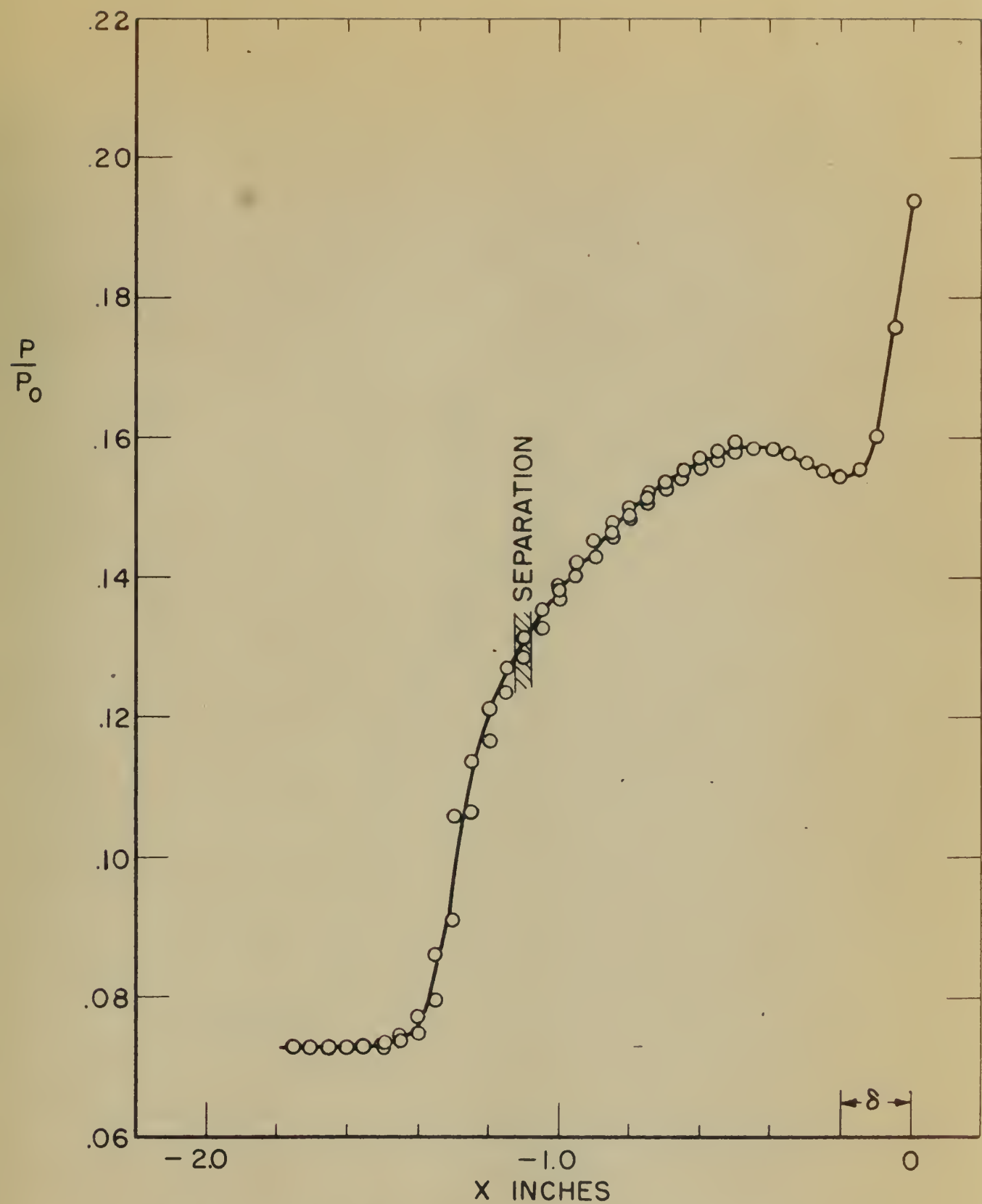
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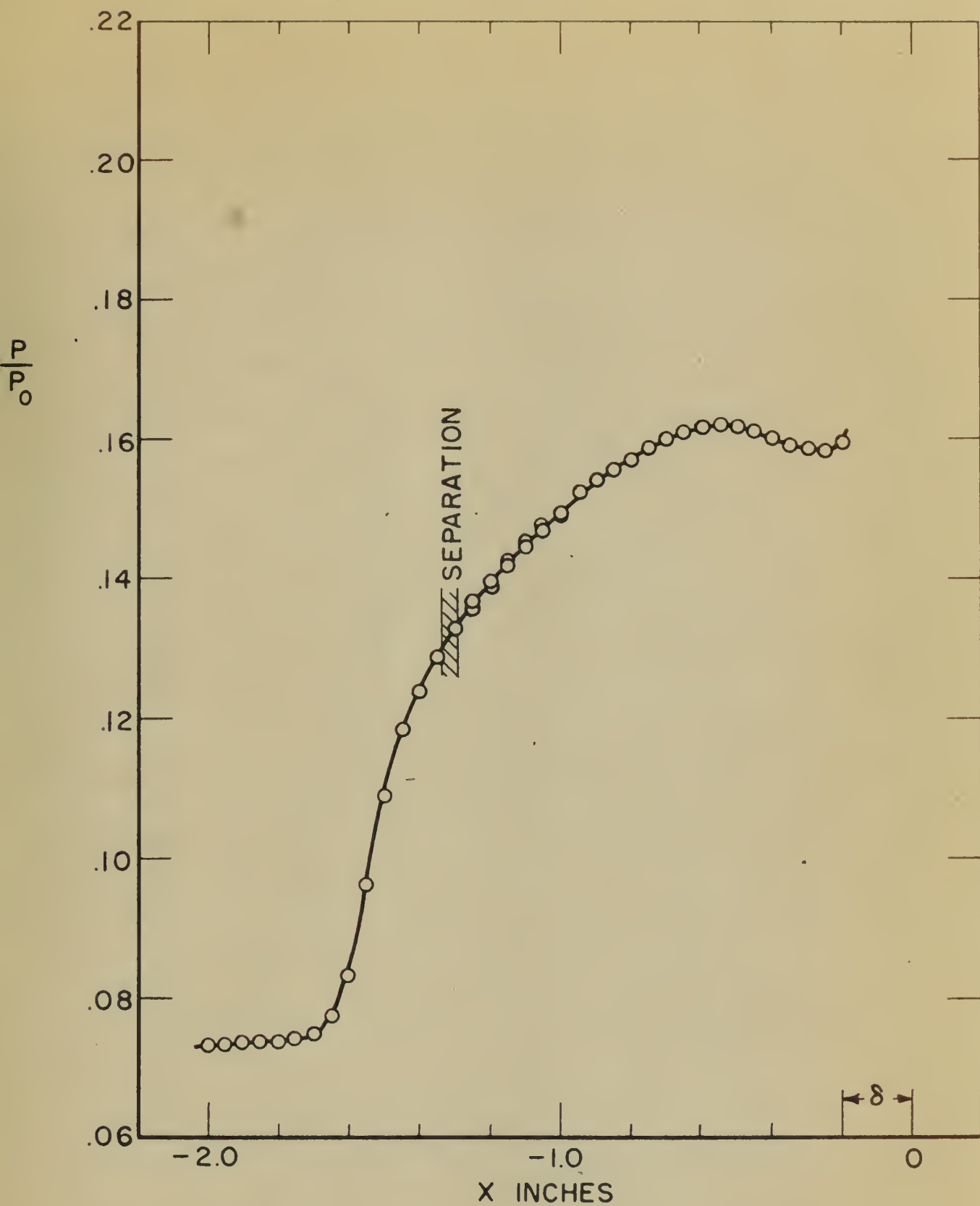
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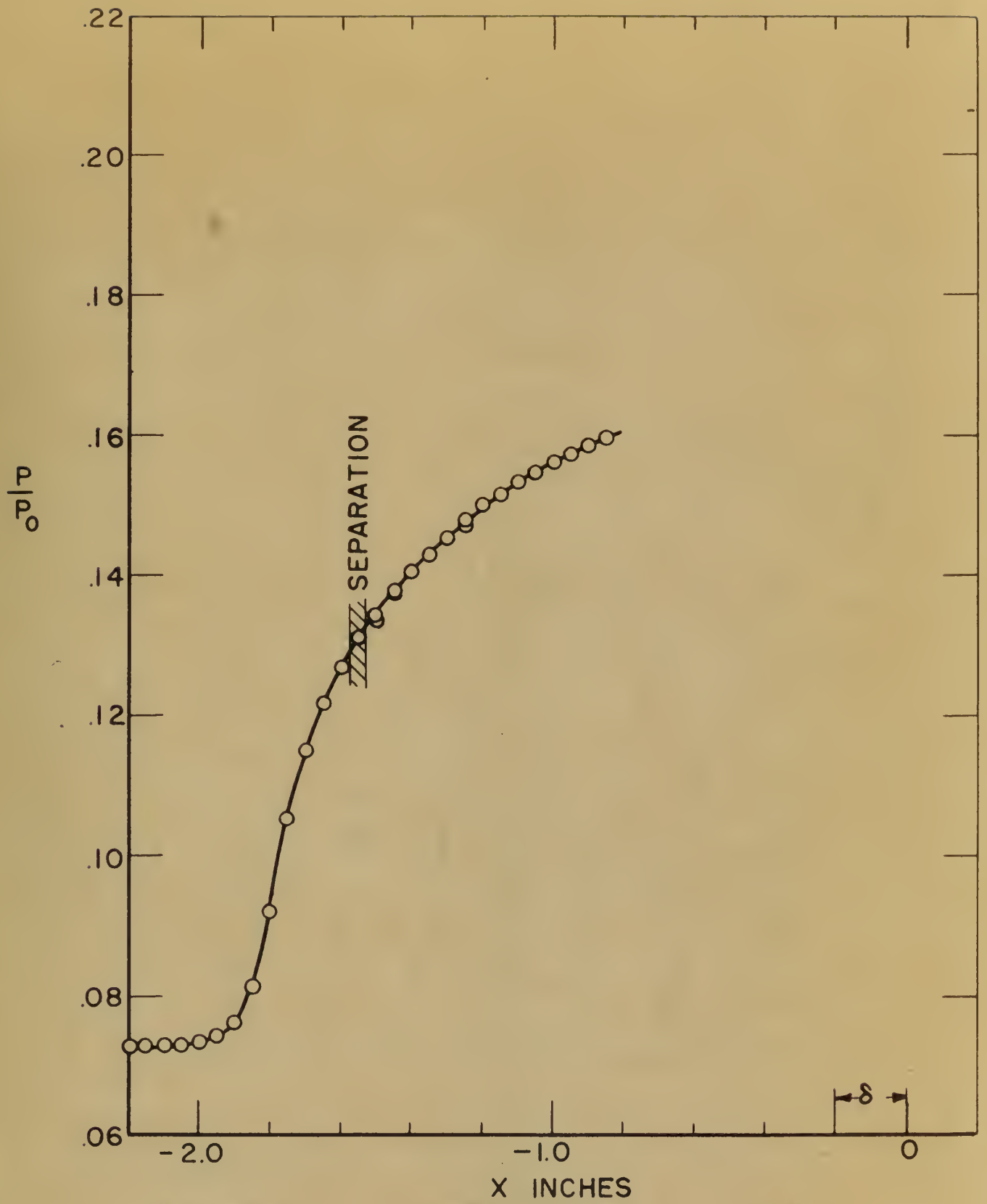
Figure Wall Static Pressure Distribution for .35" Step
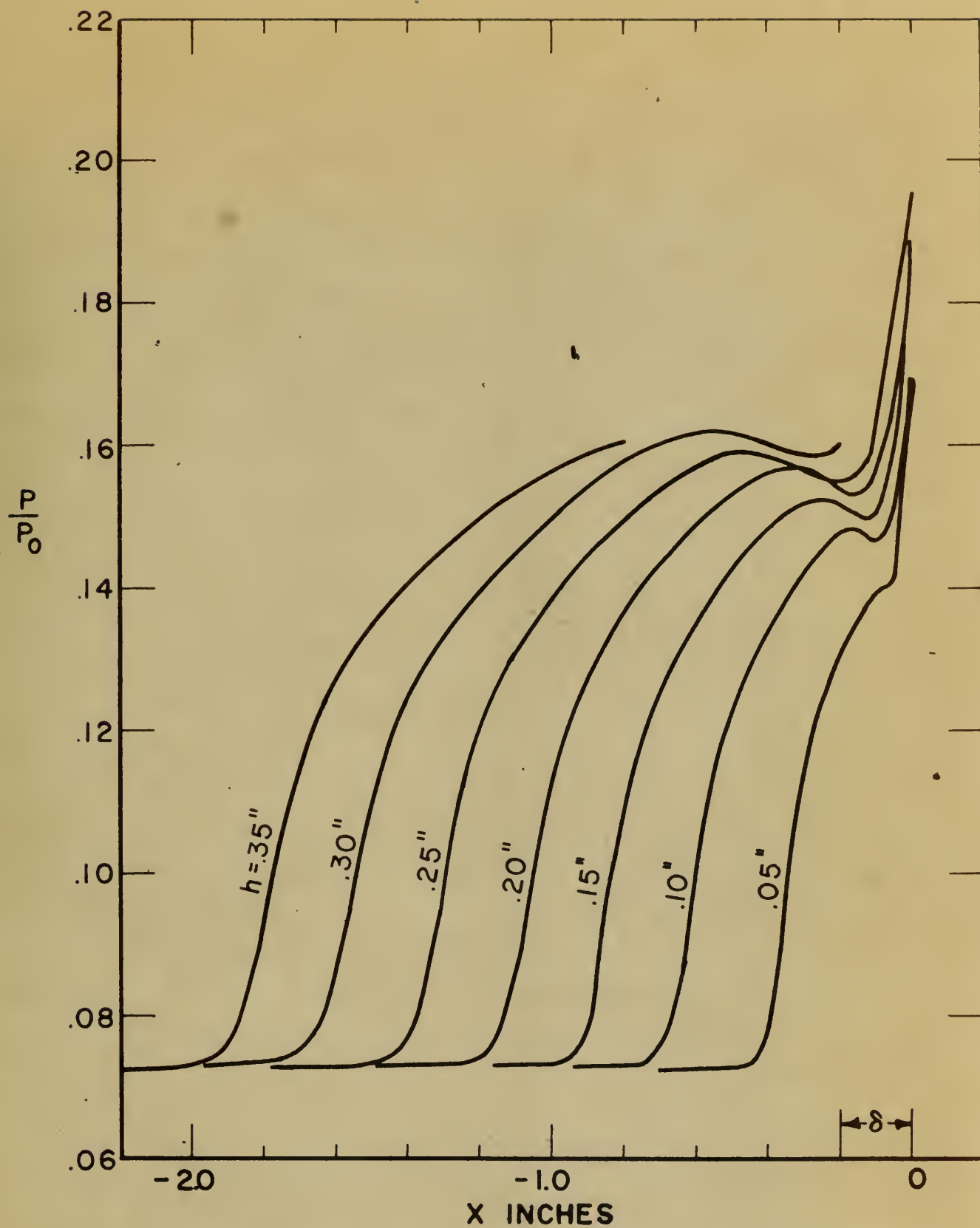
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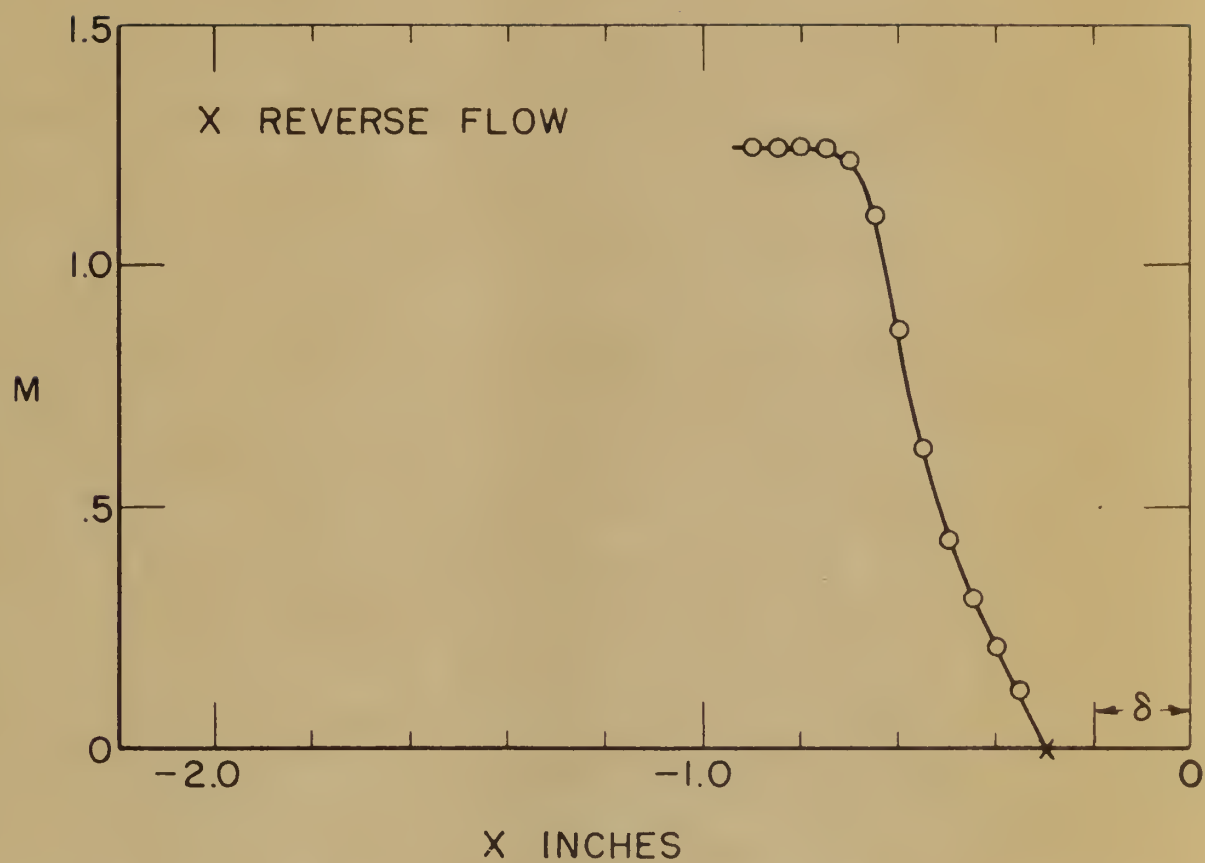
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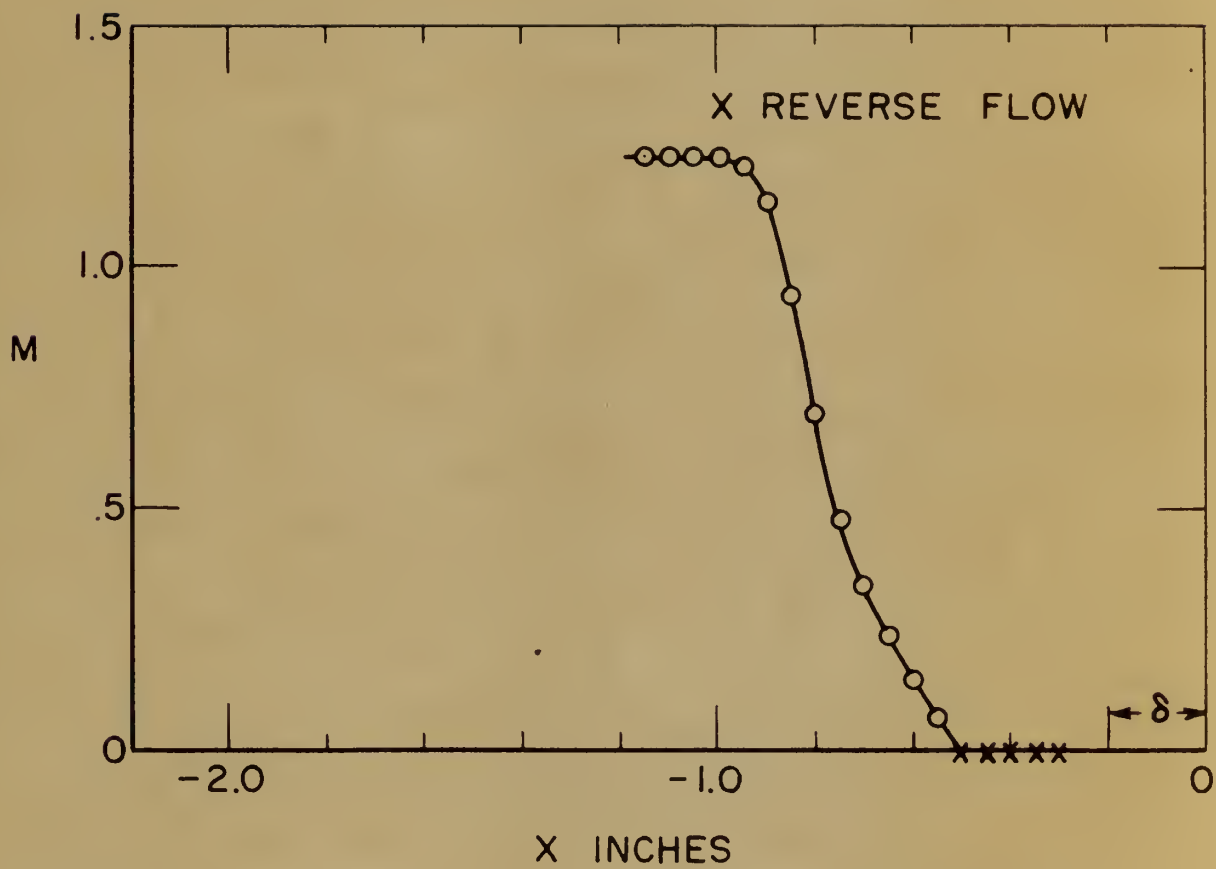
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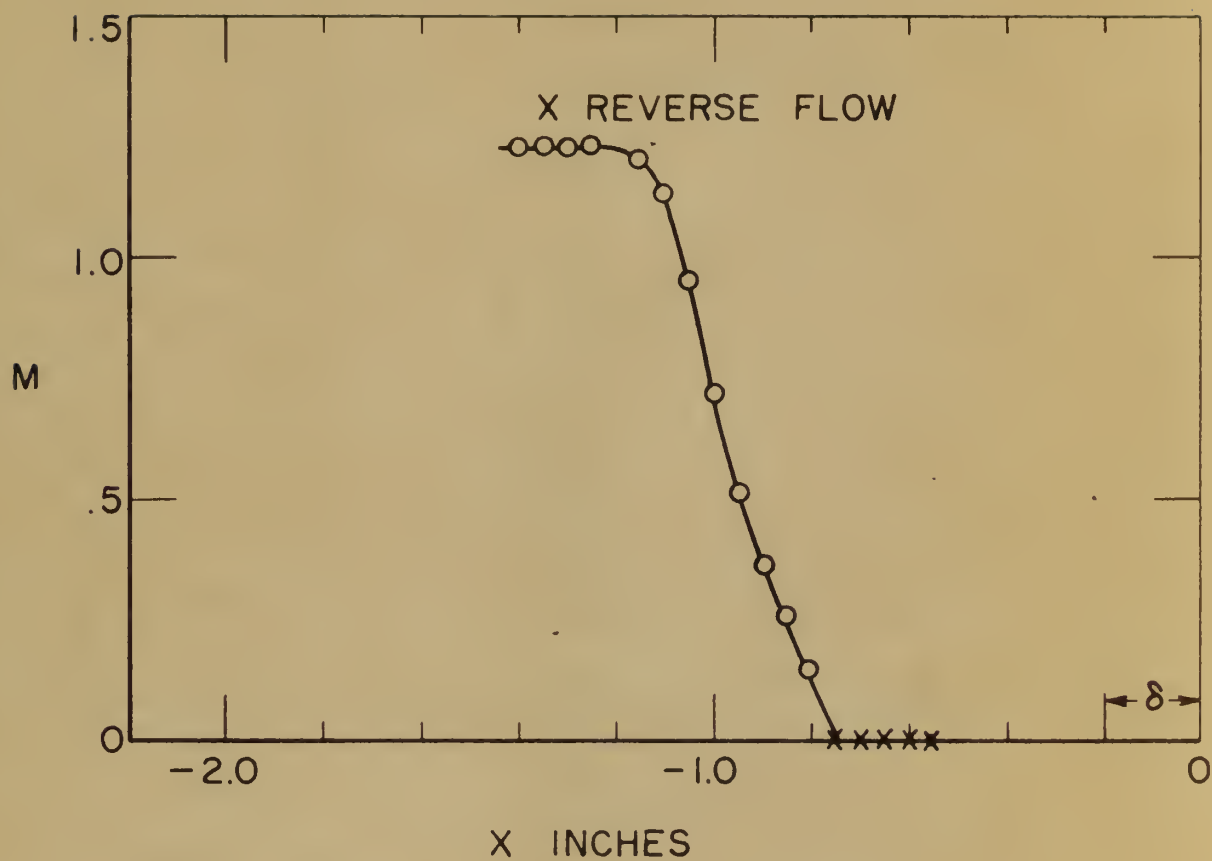
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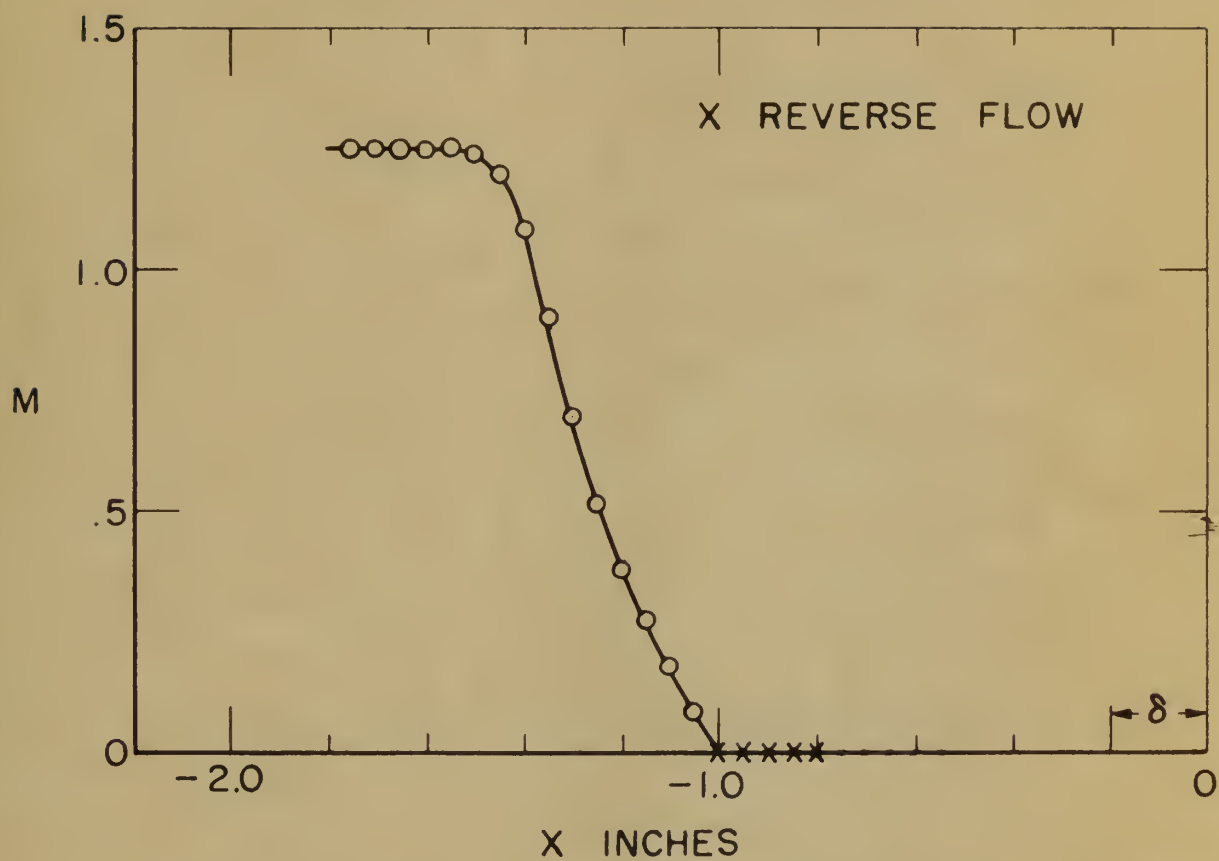
Figure 1. Mach Number Distribution .010" From Wall for .25" Step
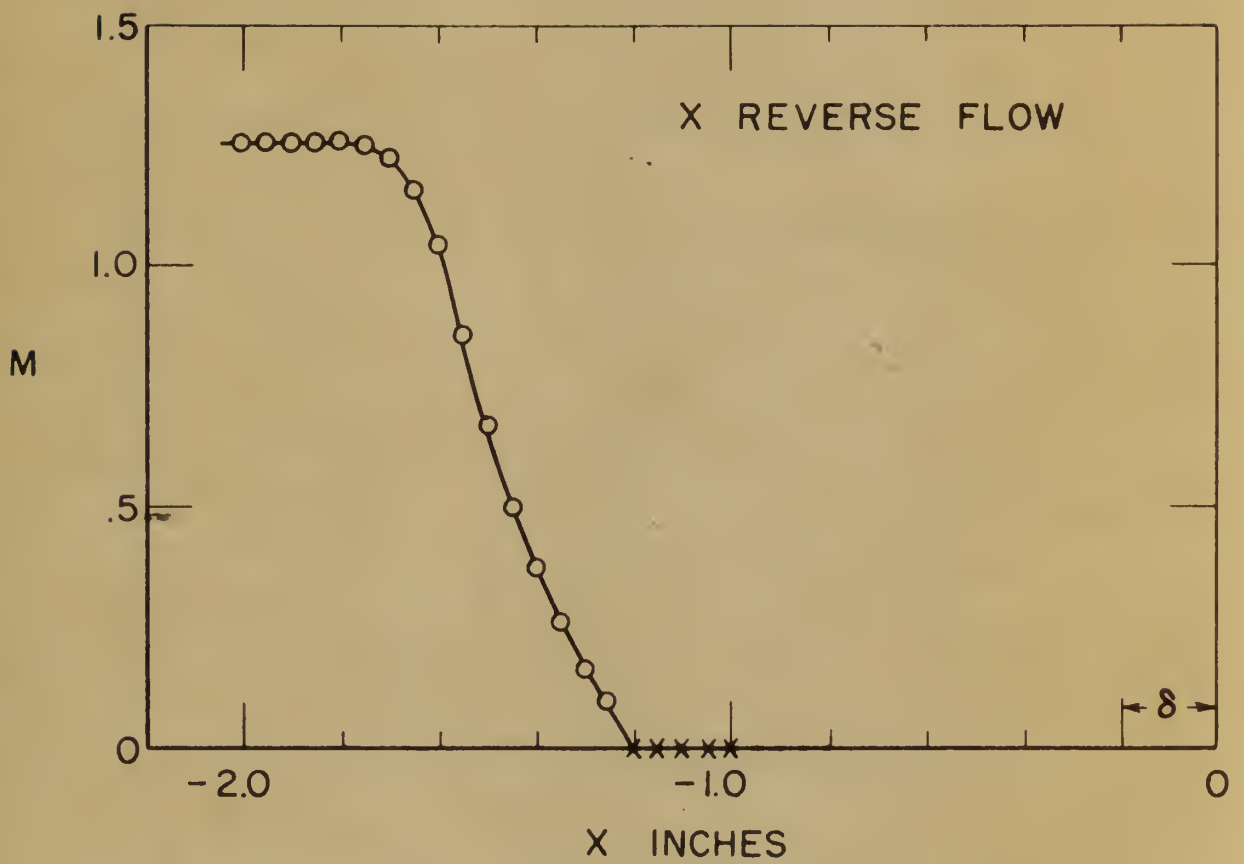
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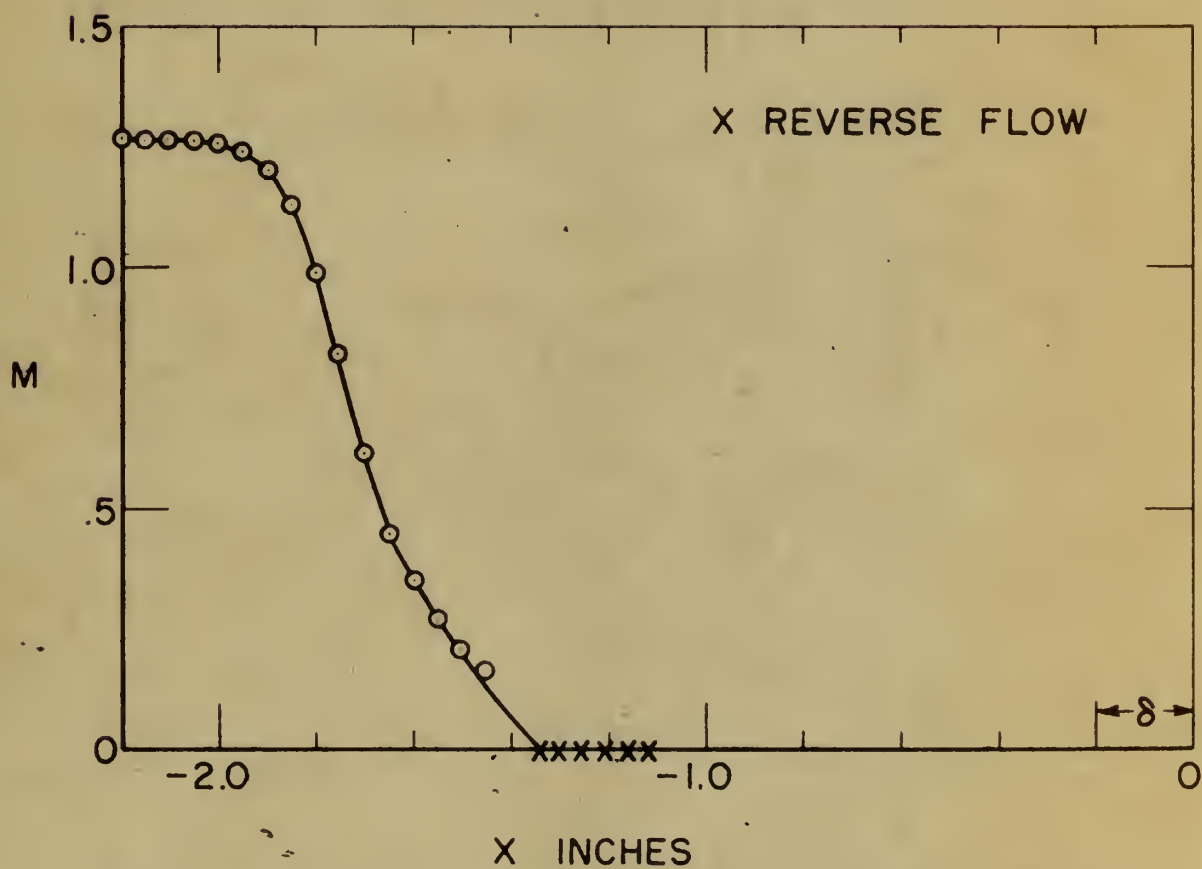
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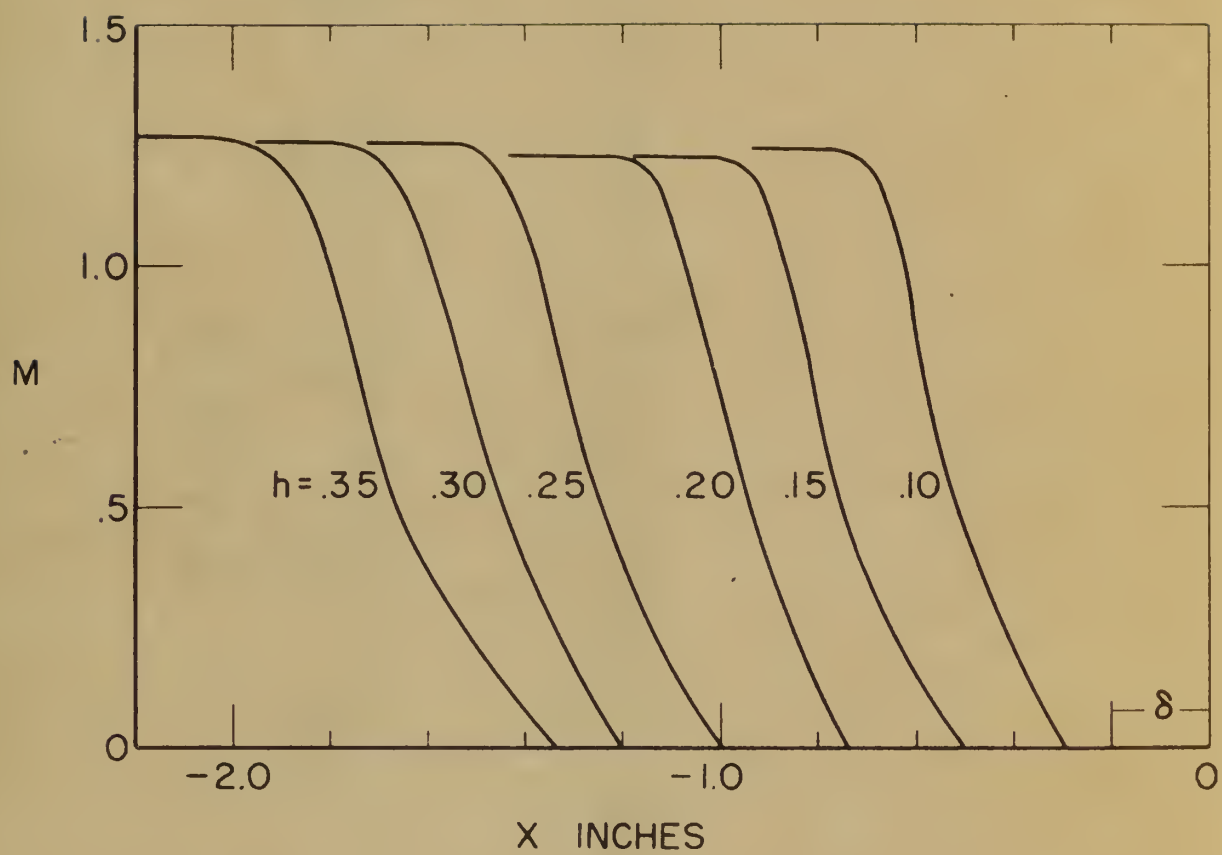
Figure 17 Composite of the Mach Number Distribution .010" From Wall
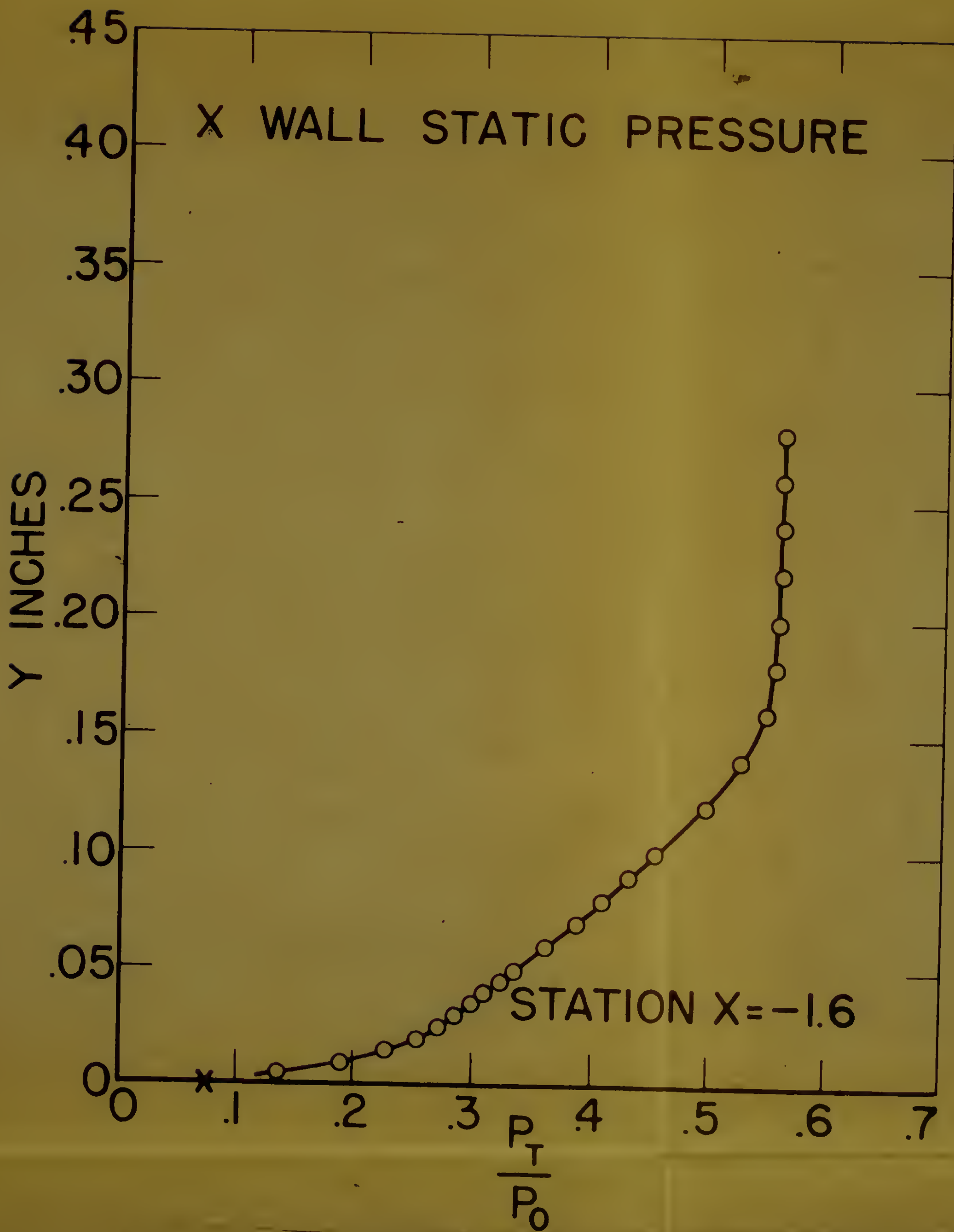
Figure 18 Total Head Profiles Through the Boundary Layer at Various Stations for .25" step
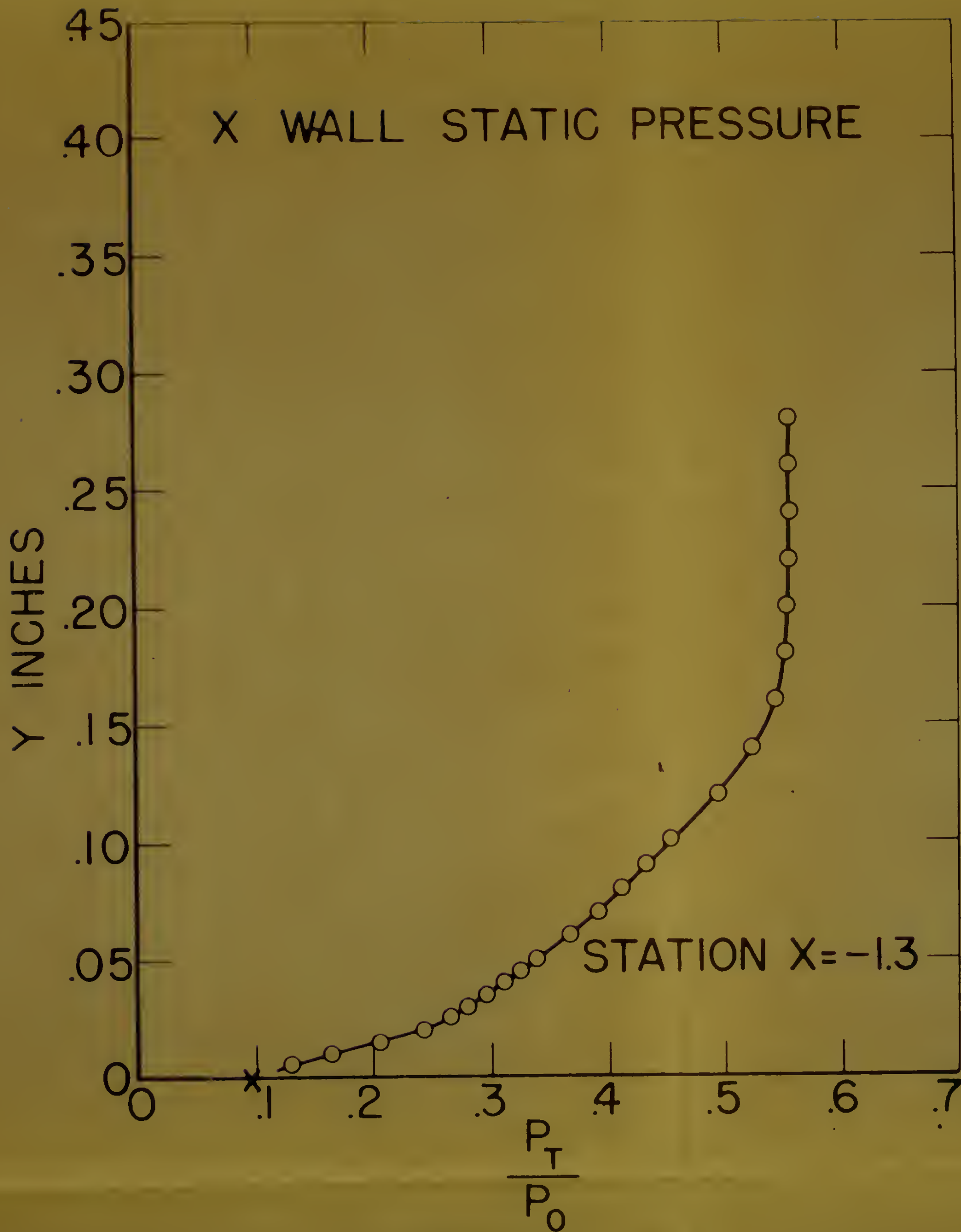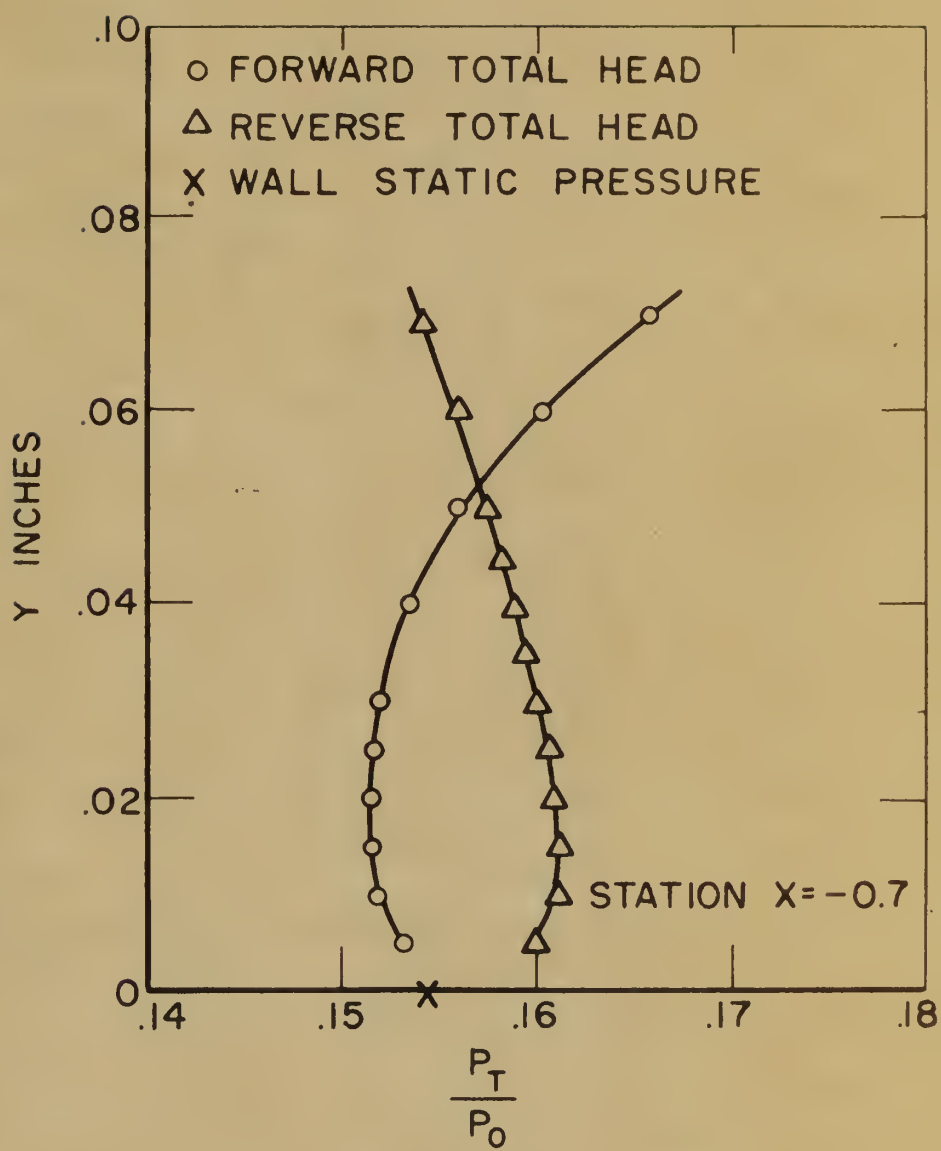
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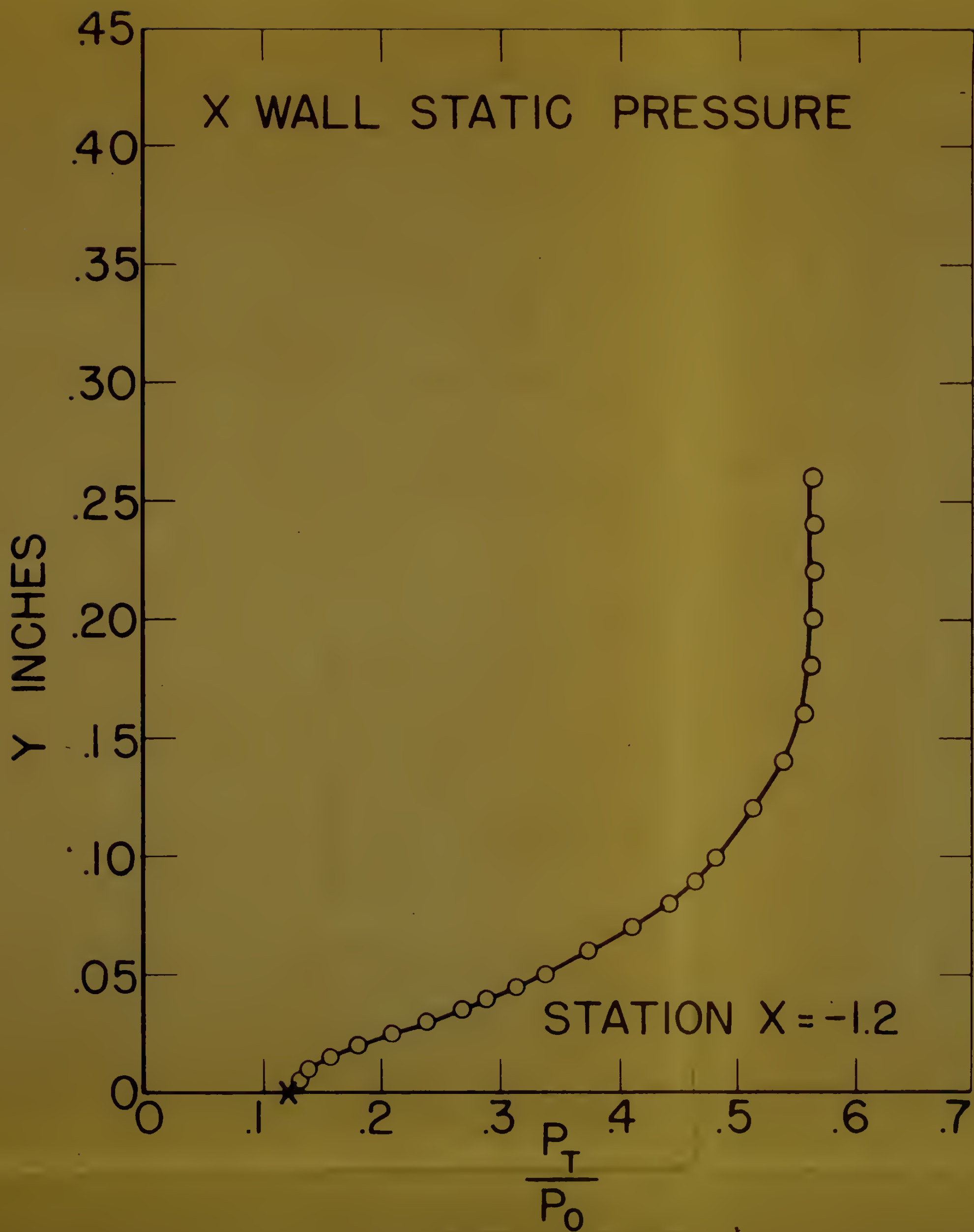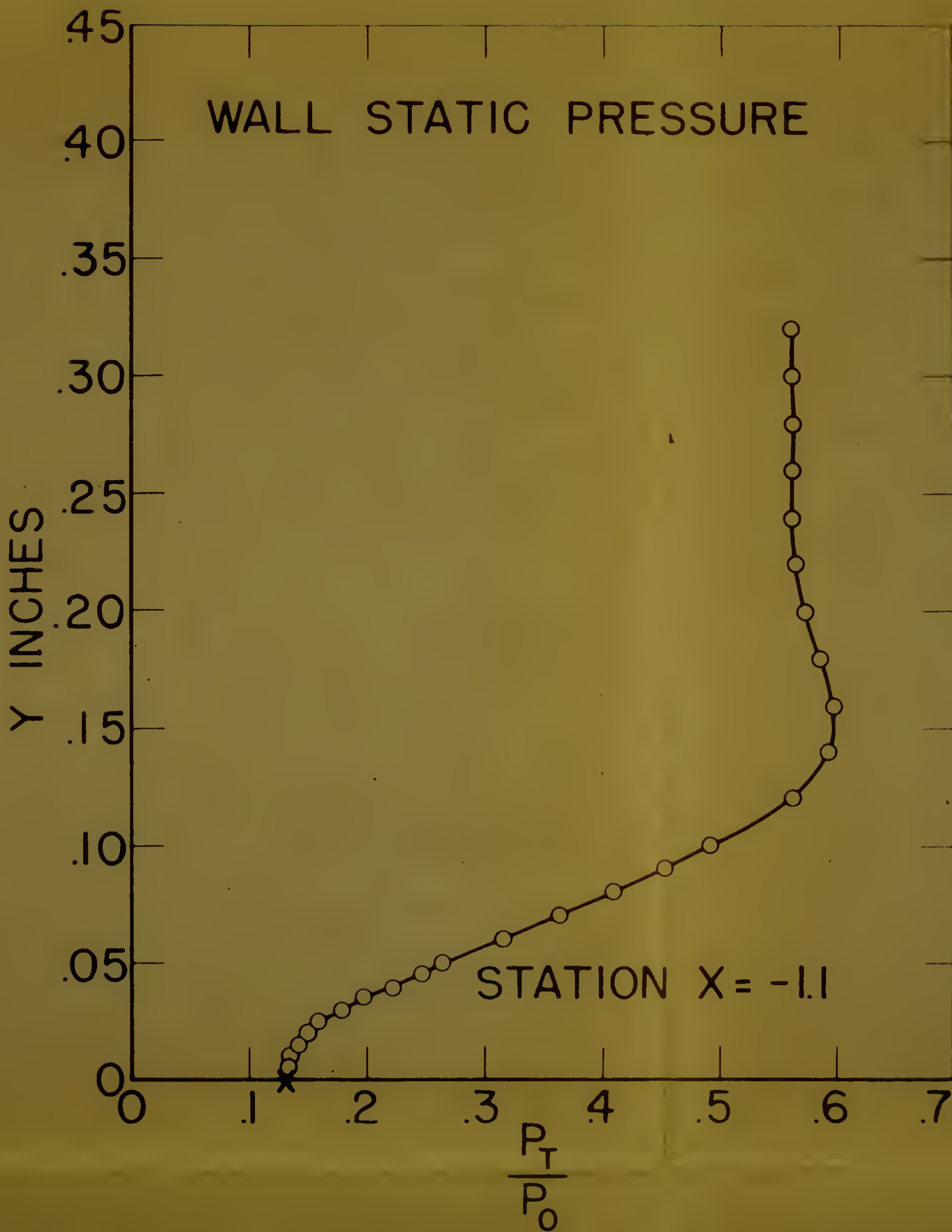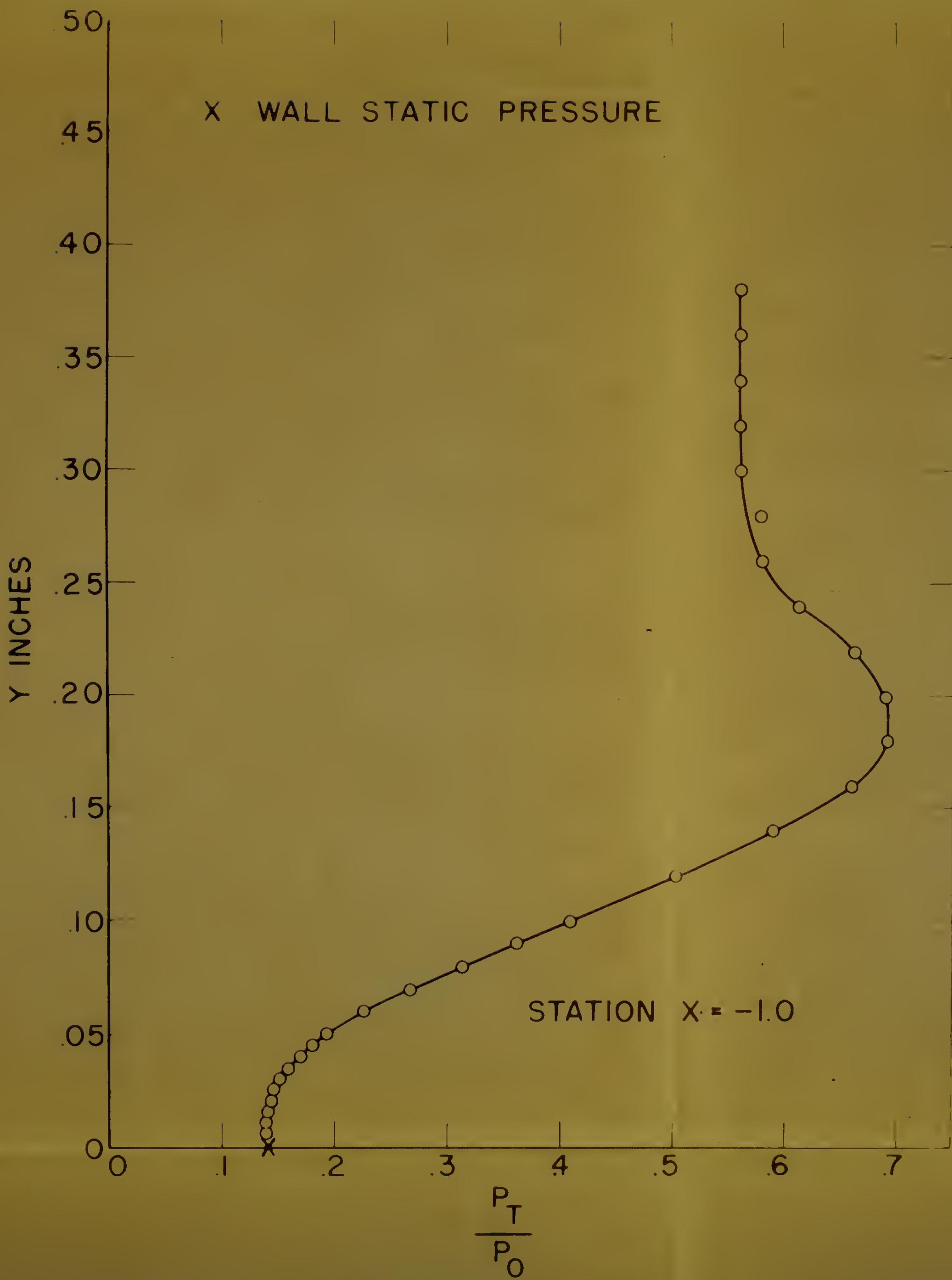
Figure 18 Continued

Figure 18 Continued

Figure 18 Continued

X WALL STATIC PRESSURE

STATION X = -0.9

Y INCHES

$$\frac{P_T}{P_O}$$

Figure 18 Continued

X WALL STATIC PRESSURE

STATION X = −0.8

$\dfrac{P_T}{P_O}$

Y INCHES

Figure 18 Continued

X WALL STATIC PRESSURE

STATION X= -0.6

Y INCHES

P_T/P_O
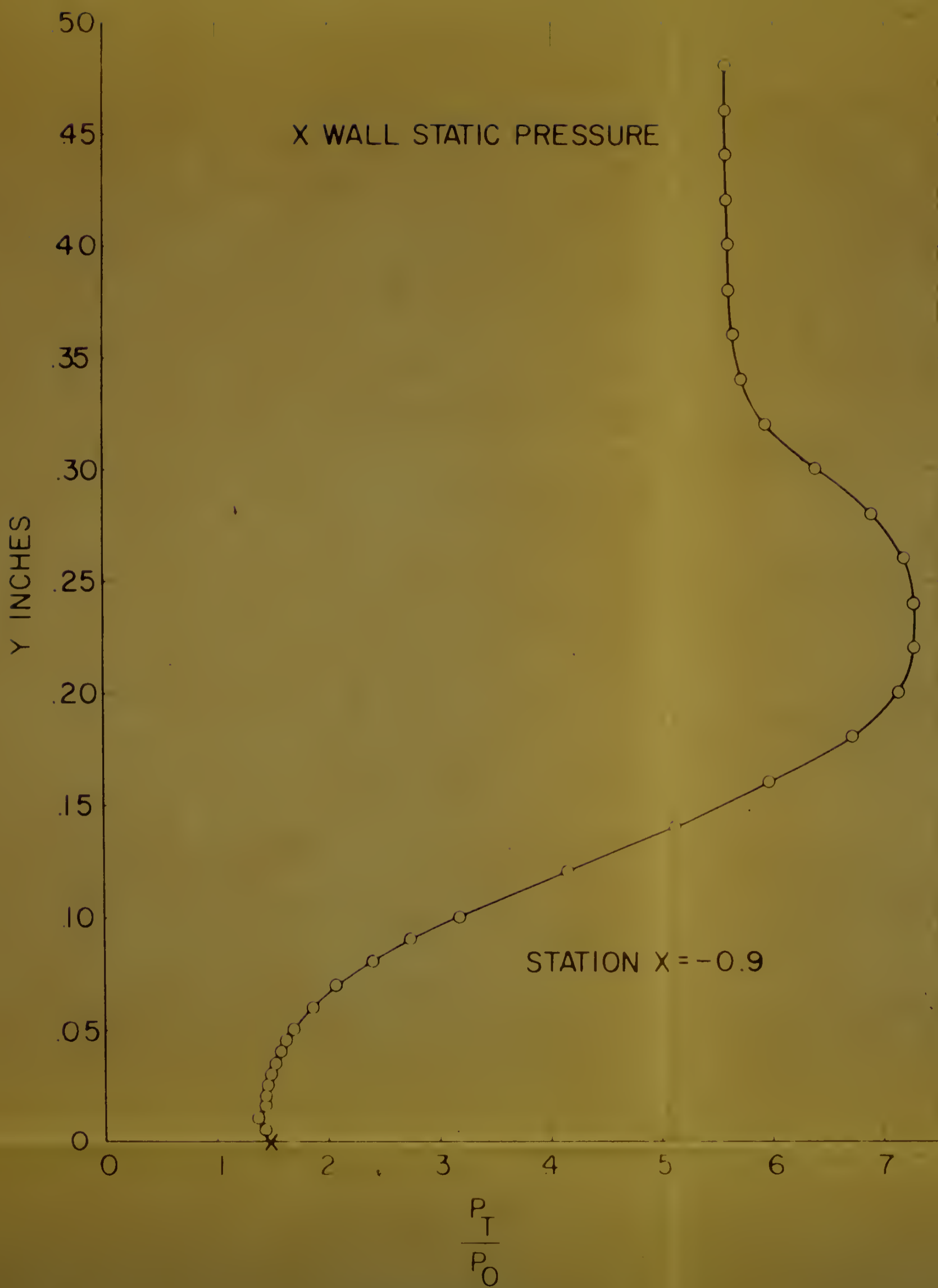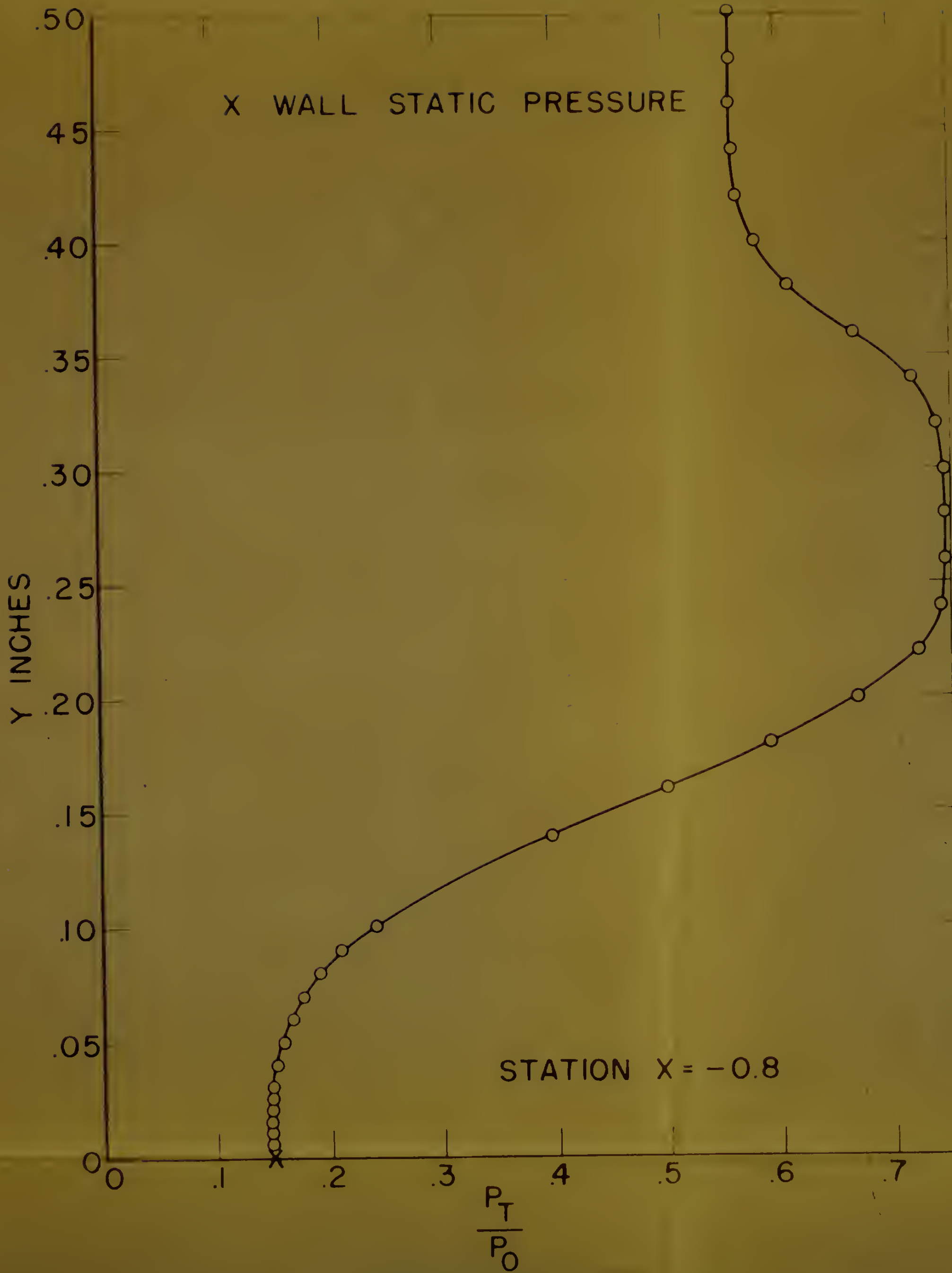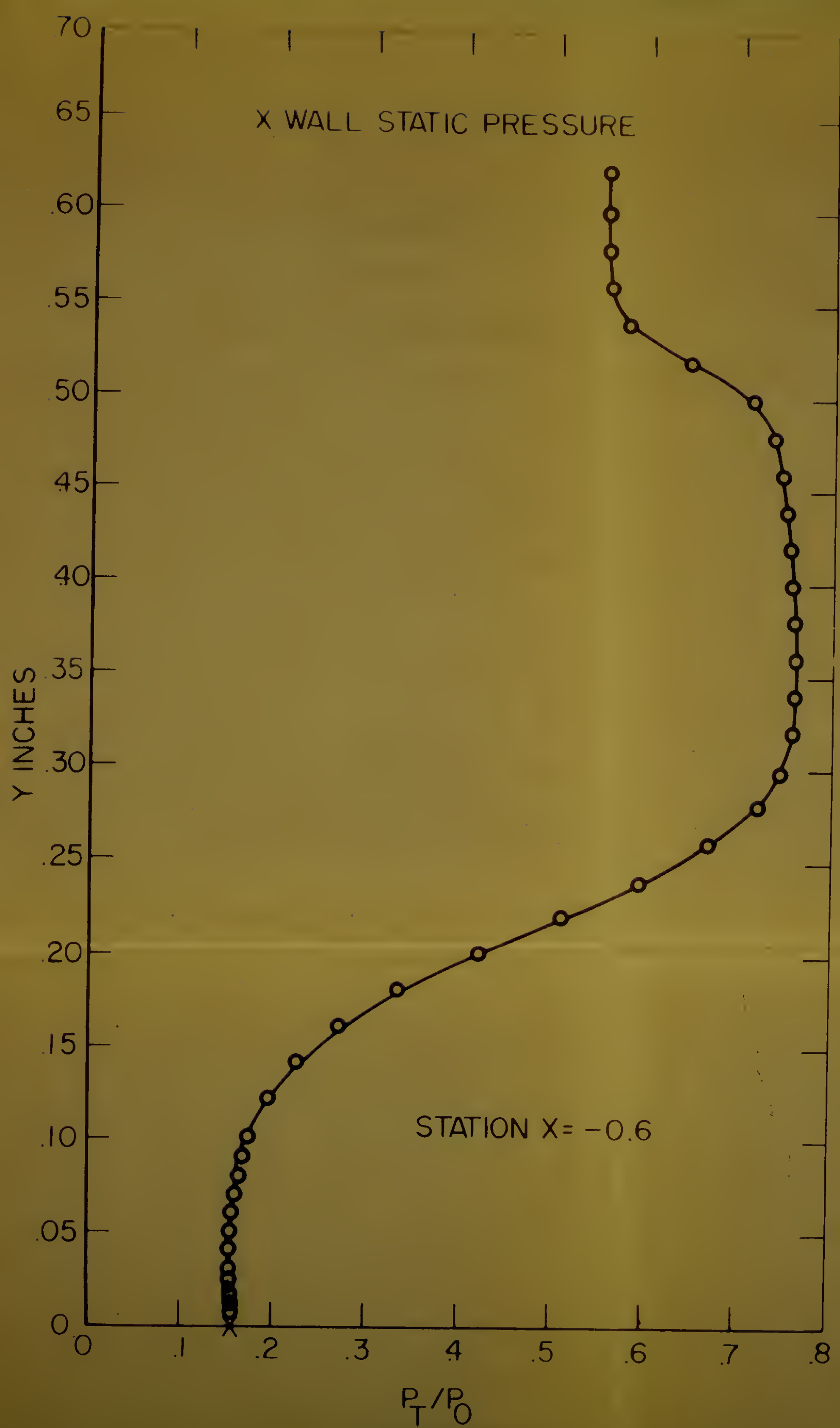
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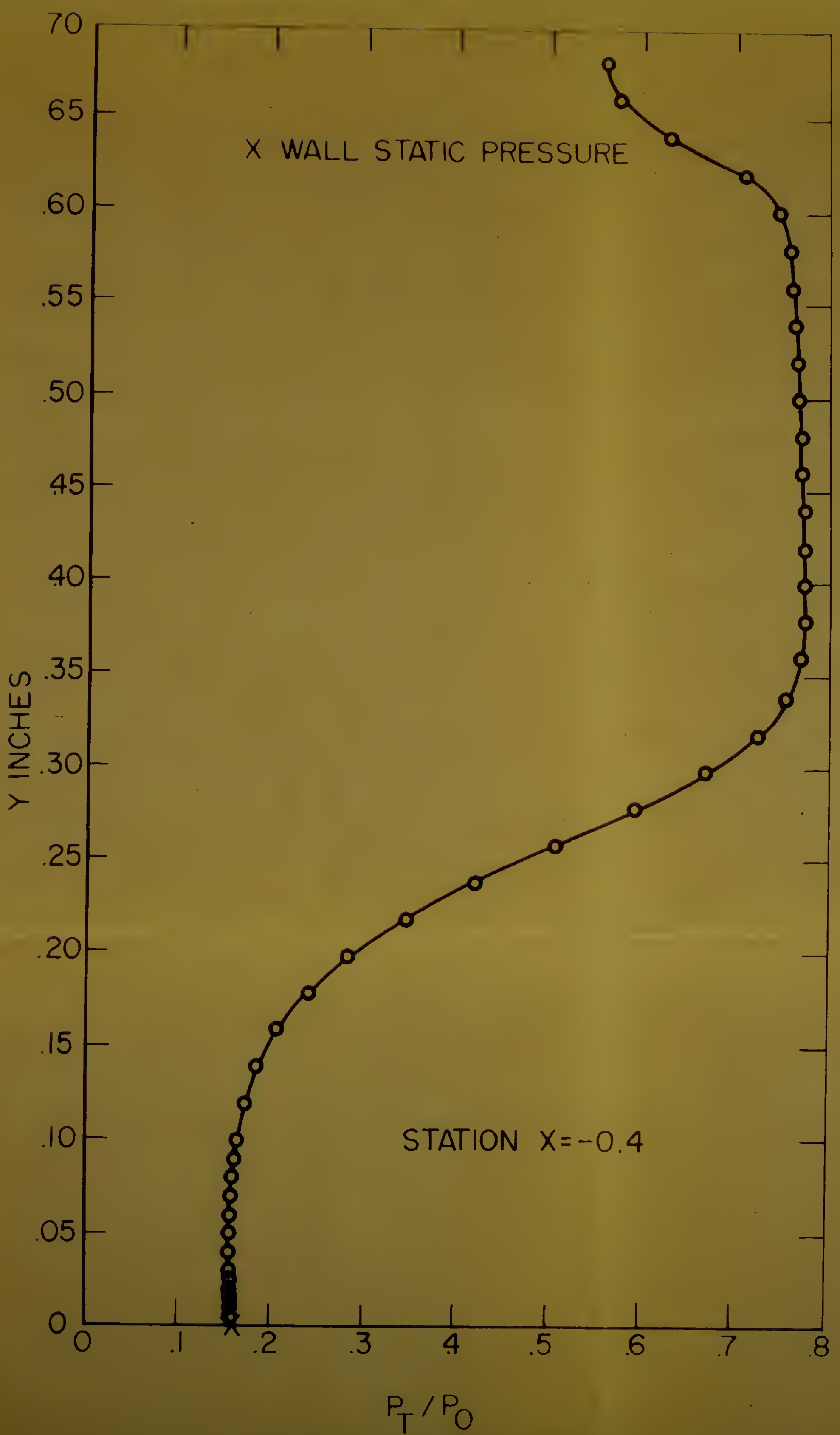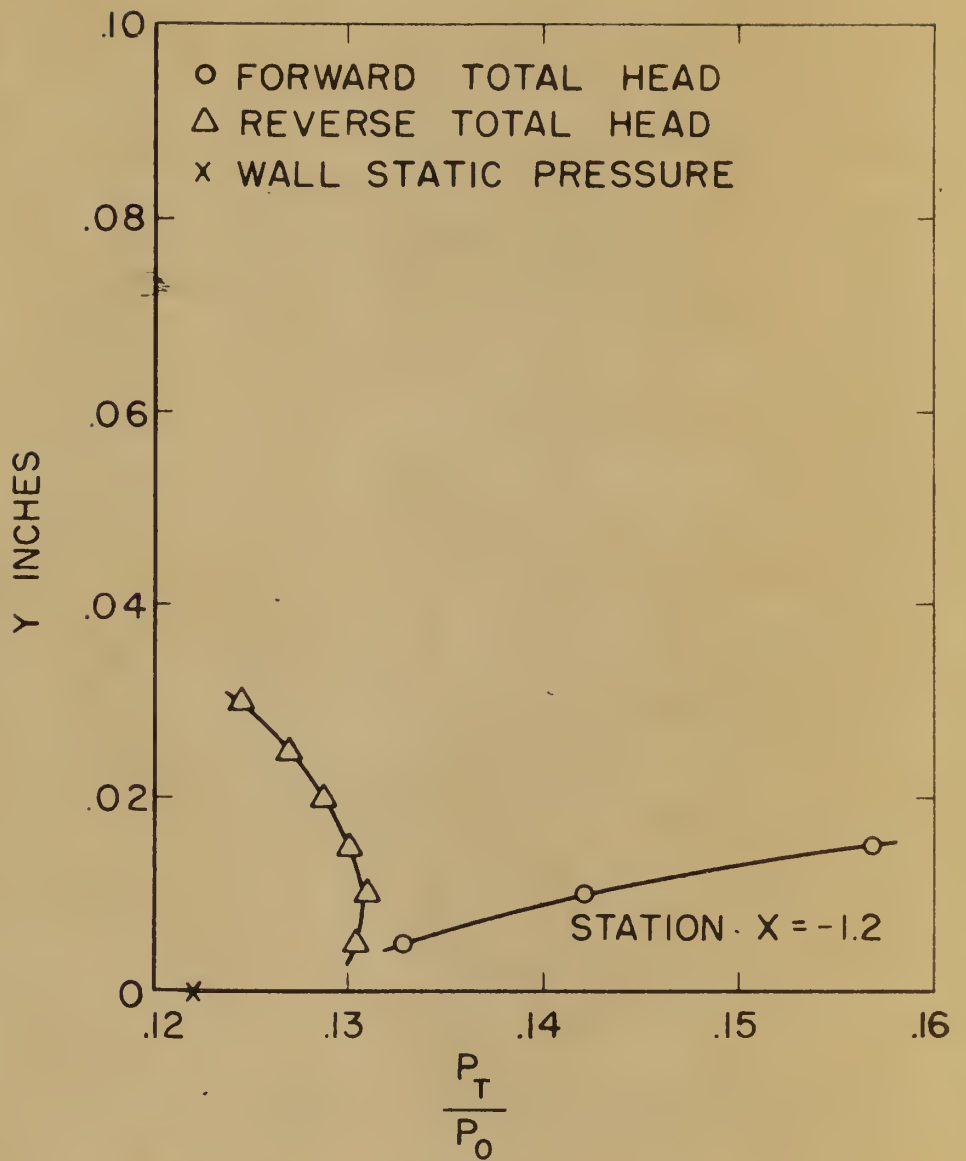
Figure 18 Concluded

Figure 1. Total Head Surveys Through Separated Regions at Various Stations for .25"
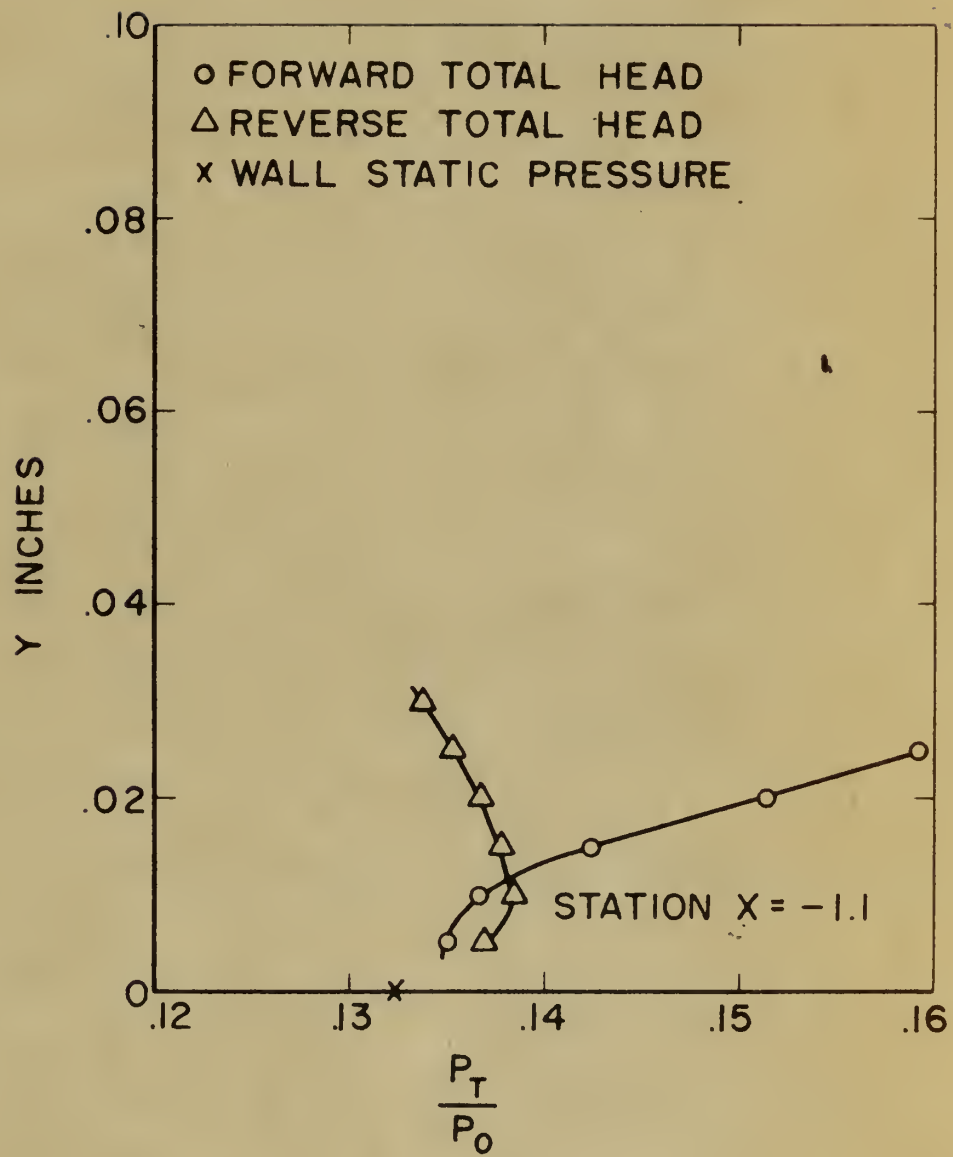
Figure 19 Continued
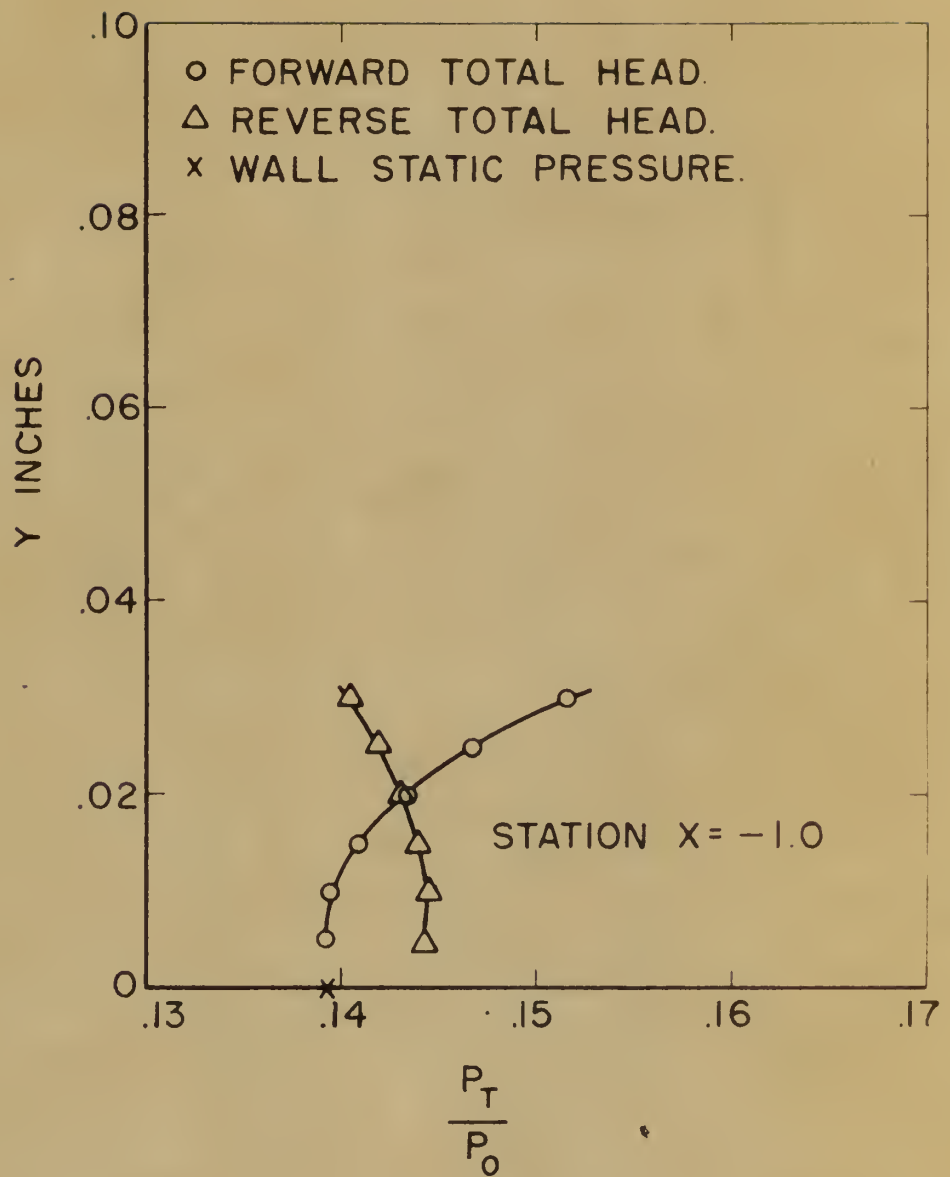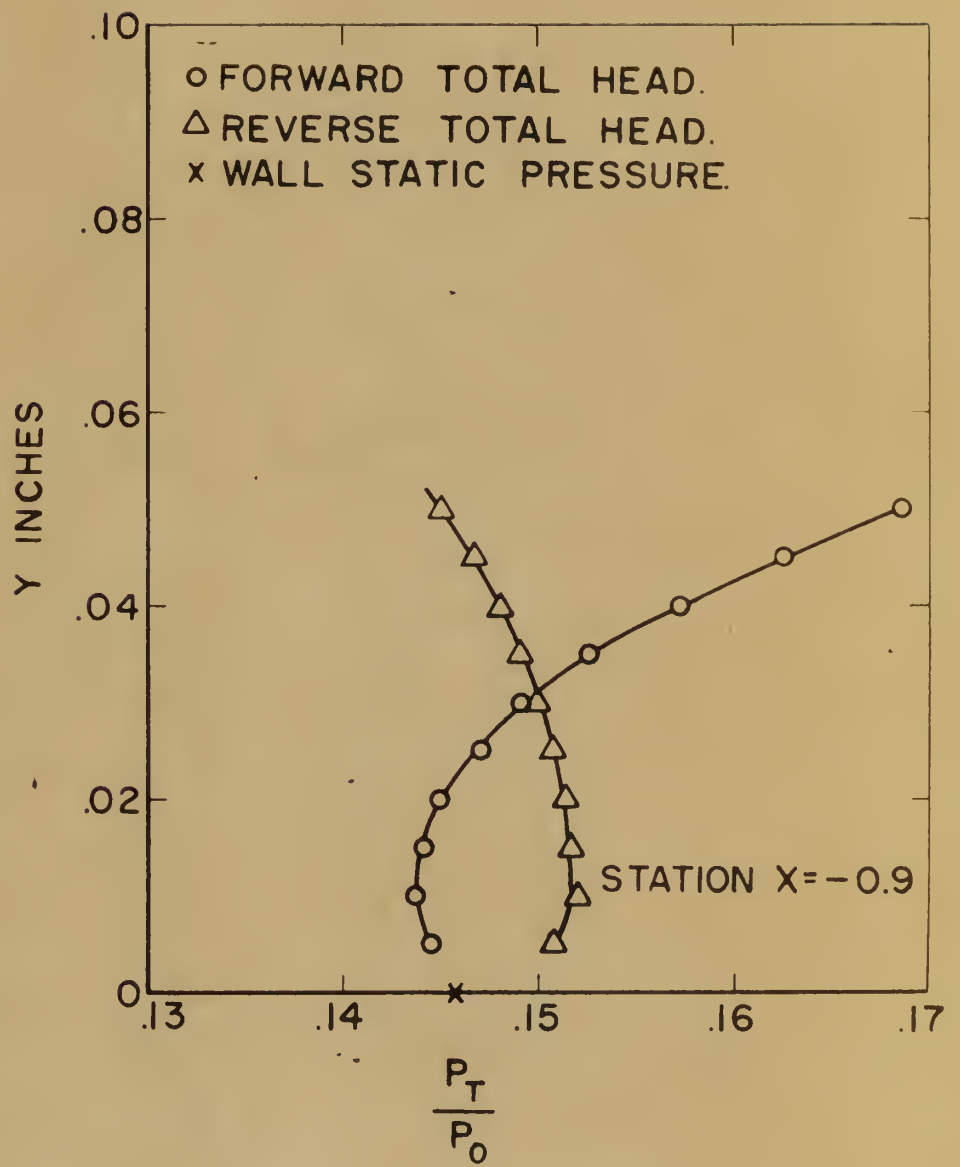
Figure 15 continued

Figure 14 Continued

Figure 1. Continued
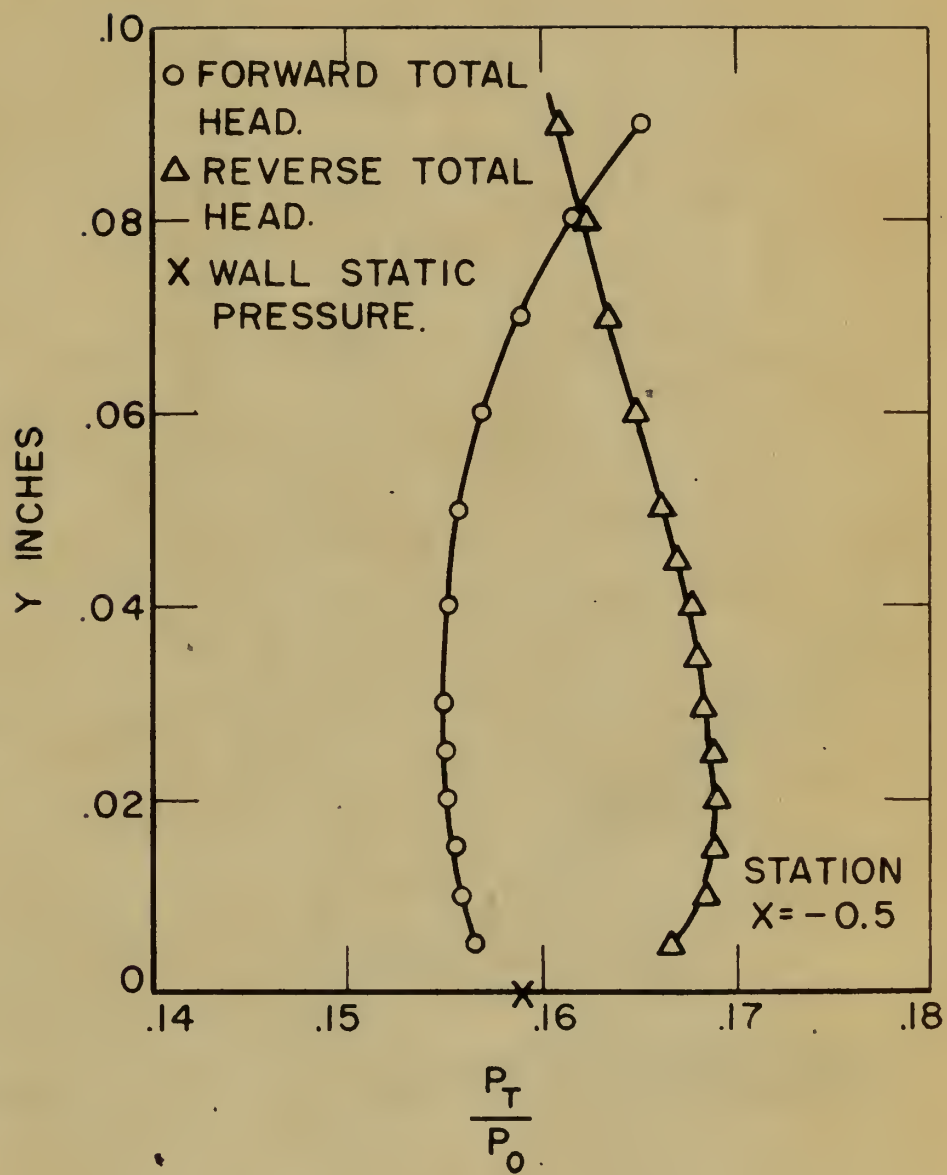
Figure 19 Concluded
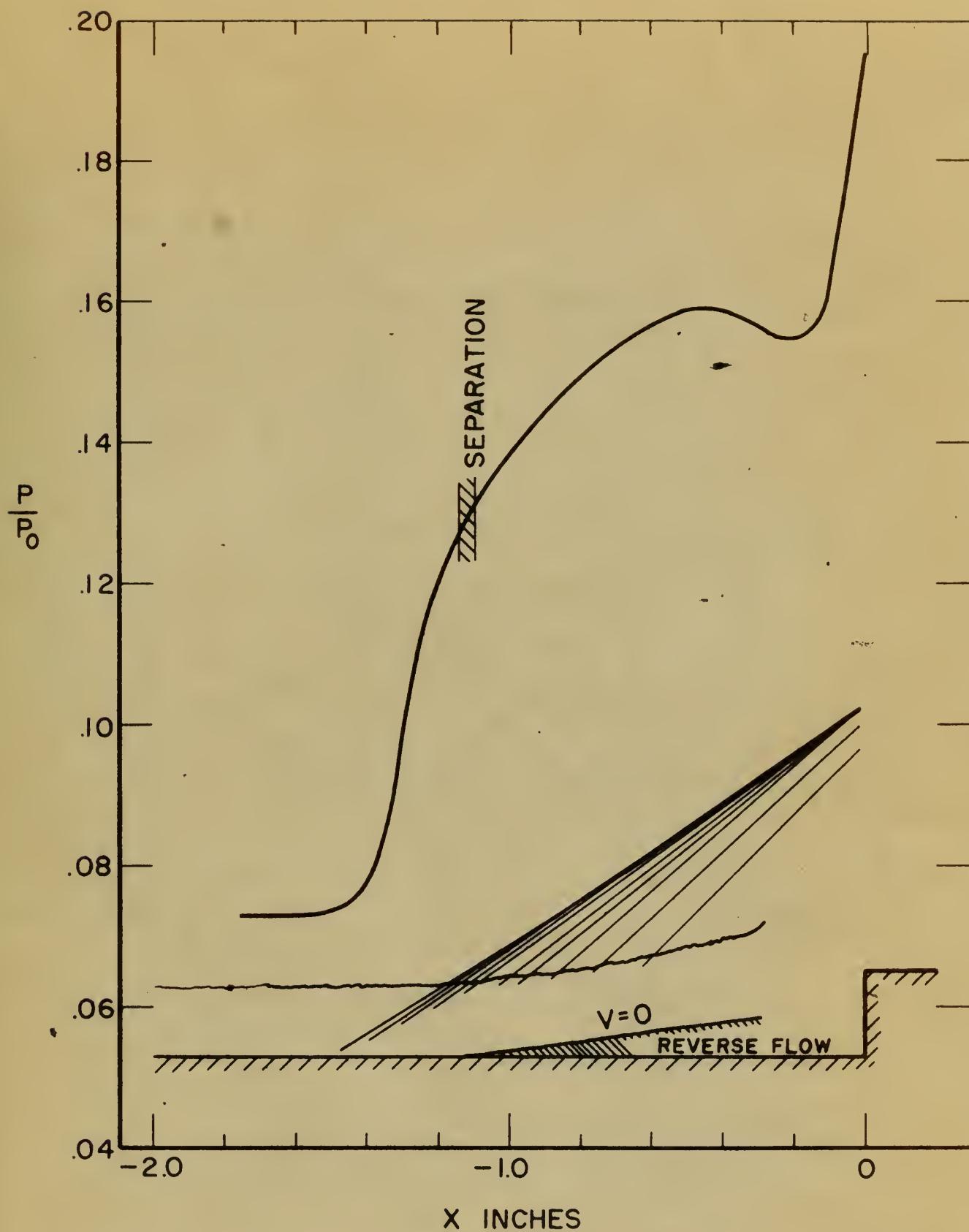
Figure 20   Schematic Drawing of Interaction for .25" Step in Juxtaposition
With the Wall Static Pressure Distribution
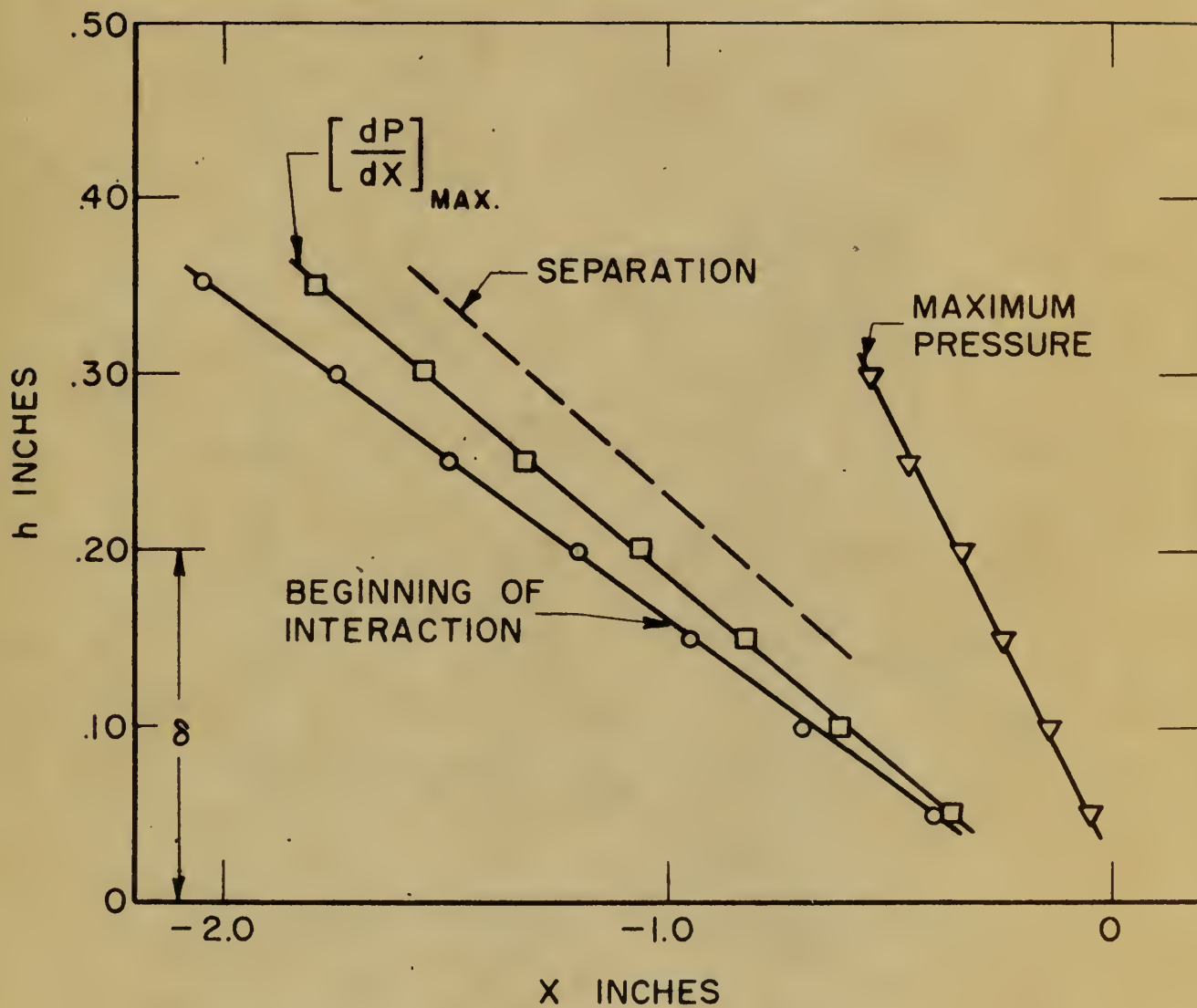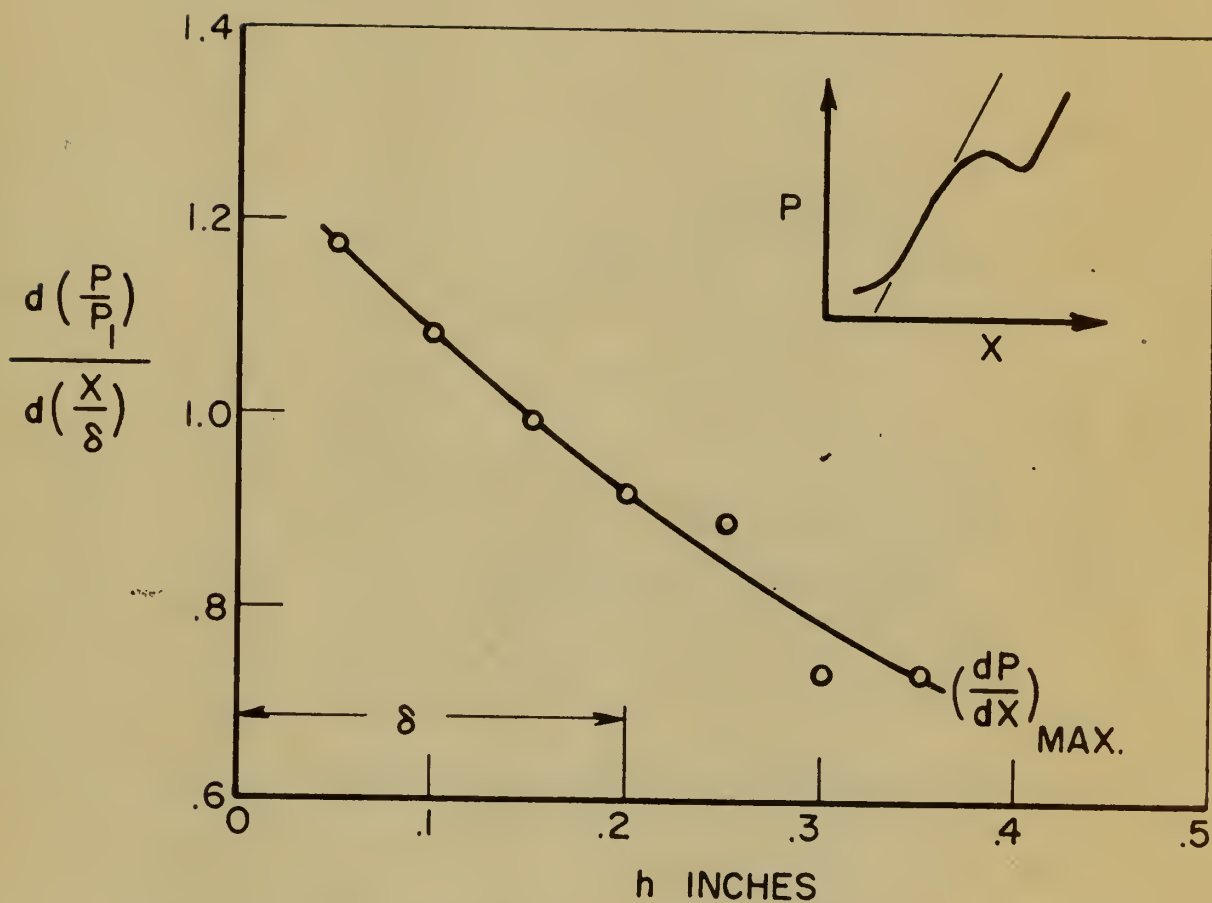
Figure 21 Interaction Regions for Various Step Heights

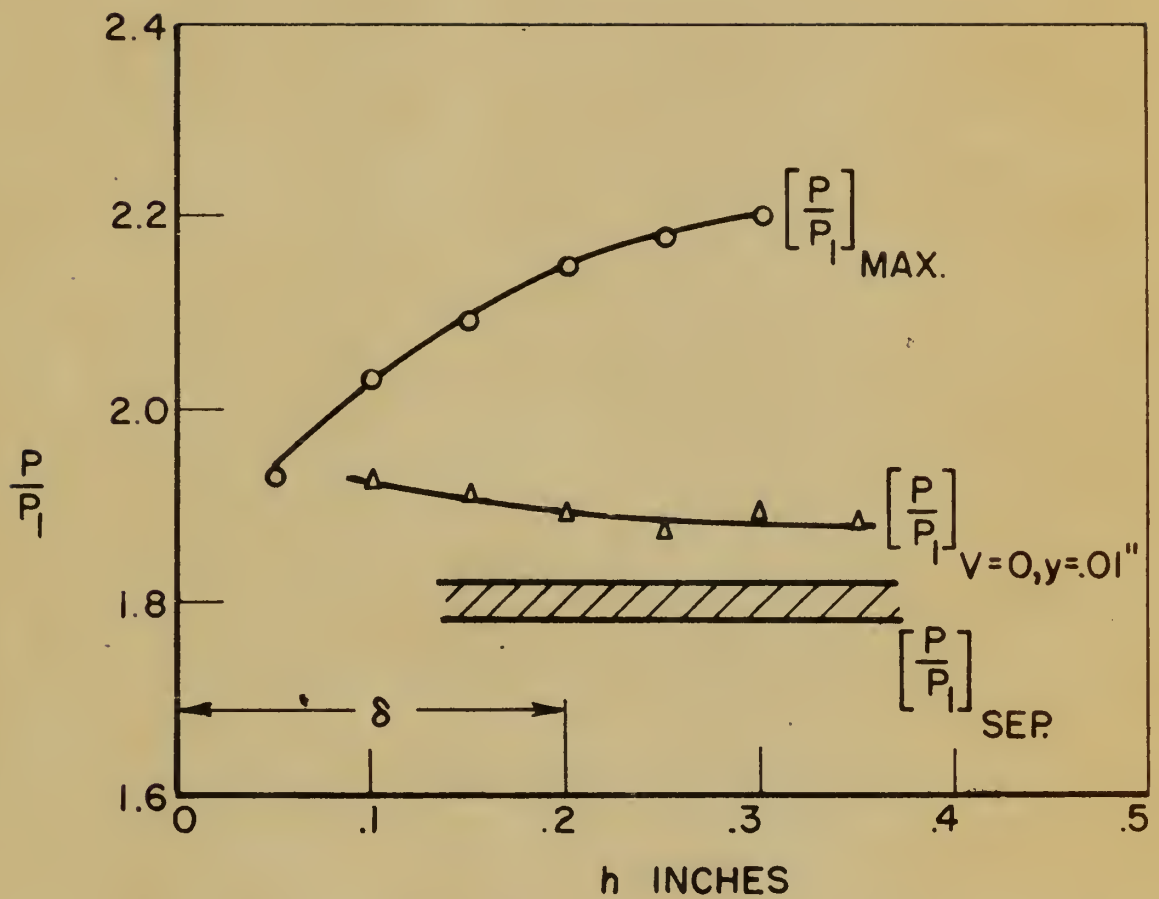Figure 22   Maximum Wall Pressure Gradients for Various Step Heights

Figure 23 Pressure Ratio at Separation and the Maximum
Pressure for Various Step Heights

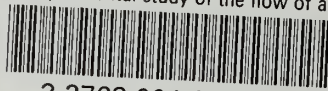W87   Wooten   28997
       An experimental study of
    the flow of a turbulent
    boundary layer over a step
    at M=2.35.